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AN EVALUATION OF INFORMATION ON VERTICAL CRUSTAL MOVEMENTS PERTAINING TO DEEP DISPOSAL

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An evaluation prepared by J.E. Gale, G. Quinlan, R. Rogerson and J. Welhan, Fracflow Consultants Inc., under contract to the Atomic Energy Control Board.

ABSTRACT

The geological and historical information on the magnitude and distribution of uplift and differential movements of rock masses as well as groundwater flow system transients that result from glacial unloading, erosion and tectonic stress have been reviewed. Data presented in the literature show that vertical crustal movements have occurred during the Cenozoic. In addition, the literature indicates significant transients exist in groundwater flow systems. The documented evidence of vertical crustal movements, plus supporting data on the stress-permeability constitutive relationships for discontinuities in fractured crystalline rocks, and three-dimensional modelling capability justifies a detailed analysis of the effects of vertical uplift on bedrock and on groundwater as they pertain to the deep disposal of radioactive waste.

RÉSUMÉ

Le présent rapport fournit les résultats d'un examen des données géologiques et historiques sur l'ampleur et la distribution des soulèvements et des mouvements différentiels des masses rocheuses, ainsi que sur les variations dans l'écoulement des eaux souterraines résultant des réajustements isostatiques dus à la fonte des glaces,aux forces tectoniques et à l'érosion. La documentation montre que les mouvements verticaux de la croûte terrestre ont eu lieu pendant le Cénozoïque. Elle fait état également des changements très importants dans les écoulements des eaux souterraines. Les données sur les mouvements verticaux de la croûte terrestre et sur les relations entre les contraintes et la perméabilité pour des discontinuités dans les roches cristallines fracturées, ainsi que la possibilité de modélisation tridimensionnelle, justifient une analyse détaillée des effets des mouvements verticaux sur la roche de fond et sur les eaux souterraines, par rapport à l'enfouissement en profondeur des déchets radioactifs.

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TABLE OF CONTENTS..... ii

ABSTRACT..... iv

A. INTRODUCTION..... 1

1. Background..... 1

2. Objectives..... 1

3. Scope and Organization..... 1

B. ANNOTATED BIBLIOGRAPHY..... 3

1. Strain Rate..... 3
1.1 Strain Rate Due to Glacial Unloading..... 3
1.2 Strain Rate Due to Erosion..... 7
1.3 Strain Rate Due to Tectonic Stresses..... 12

2. Development and Rejuvenation of Faults and Fractures Due to Glacial Loading, Erosion and Tectonic Stress..... 13

3. Fracture Frequency Due to Glacial Loading, Erosion and Tectonic Stress..... 27

4. Differential Movement of Adjacent Blocks Due to Glacial Loading, Erosion and Tectonic Stress..... 28

5. Changes in Groundwater Systems as a Result of Upward Vertical Movement..... 29
5.1 Changes in Groundwater Systems Due to Faulting and Fracturing..... 29
5.2 Changes in Groundwater Systems Due to Regional Strain and Tectonic Motion..... 30
5.3 Changes in Groundwater Systems Due to Erosional Unloading..... 31

6. Readjustment Time of Groundwater Systems Due to Changes in the Geological Environment..... 33
6.1 Groundwater Readjustment Time Pertaining to Faulting and Fracturing..... 33
6.2 Groundwater Readjustment Time Pertaining to Regional Strain and Tectonic Movement, Including Glaciation and Deglaciation..... 34
6.3 Groundwater Readjustment Time Pertaining to Erosional Unloading..... 35
6.4 Assessment and Dating of Groundwater Associated With Unspecified Processes..... 36

C. SUMMARY OF INFORMATION CONTAINED IN ANNOTATED BIBLIOGRAPHY..... 39

1. Strain Rate..... 39
1.1 Strain Rate Due to Glacial Unloading..... 39

1.1.1 Theory of Large Scale Postglacial Adjustment 39
a. Zone A Strain Rates..... 42
b. Zone B Strain Rates..... 43
c. Zone C Strain Rates..... 43
d. Zone D Strain Rates..... 43
1.2 Strain Rate Due to Erosion..... 43
1.3 Strain Rate Due to Tectonic Stresses..... 46

2. Development and Rejuvenation of Faults and Fractures by Glacial-Induced Stress and Earthquakes 48
2.1 North America..... 49
2.2 Fennoscandia..... 51
2.3 North America and Fennoscandia Compared and Contrasted..... 53

3. Fracture Frequency Due to Glacial Loading, Erosion and Tectonic Stress..... 54

4. Differential Movement of Adjacent Blocks Due to Glacial Loading, Erosion and Tectonic Stress..... 55

5. Changes in Groundwater Systems as a Result of Upward Vertical Movement..... 55
5.1 Changes in Groundwater Systems Due to Faulting and Fracturing..... 55
5.2 Changes in Groundwater Systems Due to Regional Strain and Tectonic Movement..... 56
5.3 Changes in Groundwater Systems Due to Erosional Unloading..... 56

6. Readjustment Time of Groundwater Systems Due to Changes in the Geological Environment..... 58
6.1 Groundwater Readjustment Time Pertaining to Faulting and Fracturing..... 58
6.2 Groundwater Readjustment Time Pertaining to Regional Strain and Tectonic Movement, inluding Glaciation and Deglaciation..... 59
6.3 Groundwater Readjustment Time Pertaining to Erosional Unloading..... 60
6.4 Assessment and Dating of Groundwater Associated with Unspecified Processes..... 61

D. EVALUATION OF INFORMATION ON VERTICAL CRUSTAL MOVEMENTS PERTAINING TO DEEP DISPOSAL..... 64

E. FIGURES..... 66

A. INTRODUCTION

1.1 Background

The geological conditions of an area selected for the deep disposal of radioactive wastes, must be capable of preventing the accumulation of unacceptable concentrations of radioactive substances in the biosphere which may arise as a result of radionuclide migration from a repository. In order to determine whether or not this objective can be achieved many factors need to be considered, particularly those which may affect the hydrogeological regime. Among these factors are upward, vertical, crustal movements which are occurring at the present time in the eastern half of Canada. These movements are largely due to glacioisostatic rebound following the retreat of continental ice sheets, although tectonic forces and erosion are also likely contributing to the overall uplift.

1.2 Objective

The objective of this study is to determine whether there is sufficient relevant information on the effects that upward vertical crustal movements may have on rock and on groundwater flow to allow a detailed analysis of these effects as they pertain to the deep disposal of radioactive wastes.

1.3 Scope and Organization

In this study we examined the available geological and historical information on the magnitude and distribution of uplift and differential movements of rock masses which may have resulted from glacial unloading, erosion and tectonic stress. In addition, we have examined the information that exists on changes in groundwater systems resulting from upward vertical movements. In the overall study we have given particular attention to four parameters: strain rates, the development and rejuvenation of faults and fractures, fracture frequency and the differential movement of adjacent blocks. In addition, we have examined the information on the time required for a groundwater system to adjust to changes in the encompassing geological environment.

Two major literature searches were undertaken, one for the main subject of vertical crustal movements and the second for changes in groundwater flow systems. Both searches were run on the Georef system and utilized a number of main key words and related control words. These two searches produced very little information that was not already available to the authors. Hence most of the information contained in this report, including both domestic and international data, were obtained from the personal files of the authors, including both published and unpublished papers and reports.

The relevant information obtained from this study is first

presented in the form of an annotated bibliography followed by a summary, arranged by topic. While an in-depth evaluation of the collected information was beyond the scope of this study, the final chapter of this report is an evaluation of the information and data collected in terms of whether or not a detailed analysis of the effects of vertical uplift on bedrock and on groundwater as they pertain to the deep disposal of radioactive waste is justified.

B. ANNOTATED BIBLIOGRAPHY

1. Strain Rate

1.1 Strain Rate Due to Glacial Unloading

Adams, J., 1981. Postglacial faulting: a literature survey of occurrences in eastern Canada and comparable glaciated areas. Atomic Energy of Canada Ltd. Technical Record TR-142, 63 pp.

A detailed literature search of postglacial faulting documenting evidence for faulting on various spatial scales. The bulk of such faults have small throws on the order of tens of mm but may occur as sets having cumulative offset of 1 - 2 m. Faults with throws comparable to the postglacial faults of Scandinavia appear to be rare with only two examples being cited. This should serve as a note of caution against accepting the Fennoscandian estimates of Henkel et al. (1983) at face value. Why should the faulting patterns be so different in Fennoscandia and eastern Canada when the glacial loading patterns were so similar?

Barnett, T.P., 1983. Recent changes in sea level and their possible causes. Climatic Change, vol. 5, pp. 15-38.

An analysis of global tide gauge networks showing a recent rise in the average depth of the oceans over and above what can be accounted for by residual postglacial effects. The rate of rise is on the order of 15 cm/century. The author feels that the explanation of this rise in terms of thermal expansion of the oceans may be incorrect because the sea surface temperature data are possibly biased toward an increasing trend that may not be real.

Basham, P.W., Forsyth, D.A., and Wetmiller, R.J., 1977. The seismicity of northern Canada. Canadian Journal of Earth Sciences, vol. 14, pp. 1646-1667.

A catalogue of seismicity in northern Canada with speculation as to the relation between seismicity and postglacial rebound.

Cathles, L.W., 1975. The Viscosity of the Earth's Mantle. Princeton University Press, Princeton, N.J., 386 pp.

A valuable textbook on the mechanical response of the Earth to the forces of glaciation. The ideas of this book have been incorporated into more recent models by Peltier, Farrell and Clark and Quinlan and Beaumont. Many observations on postglacial rebound are documented.

Clark, J.A., 1976. Greenland's rapid postglacial emergence: A result of ice-water gravitational attraction. Geology, vol. 4, pp. 310-312.

The author analyses the influence of gravitational attraction between a continental ice sheet and the surface of the ocean. He establishes that during times of glaciation the depth of water near the periphery of ice sheets may in fact increase despite the overall global lowering of sea level. Melting of ice sheets removes the attracting mass and allows water depth to drop drastically near the former ice sheet periphery. This effect could easily be interpreted erroneously as being due to very rapid postglacial uplift of the deglaciated landmass.

Farrell, W.E. and Clark, J.A., 1976. On Postglacial sea level. Geophysical Journal of the Royal Astronomical Society, vol. 46, pp.647-668.

This paper describes a global model of postglacial relative sea level in which all important physical aspects of the problem have been included. It defines the integral equation necessary to calculate the relative sea level record at any site around the world in response to the melting of any arbitrary global ice reconstruction. This model provides the means of evaluating any proposed ice reconstruction on the basis of whether or not its consequences are consistent with observed relative sea level record. Modifications of this model provide the basis of all recent theoretical analyses of postglacial rebound.

Flint, R.F., 1971. Glacial and Quaternary Geology. John Wiley and Sons, 892 p.

A good general textbook on glacial geology. Although a bit out of date on many topics, it is a good source of general information such as the timing and extent of ice sheets. However, even this information is dated and generally falls within the 'maximum' concept of extent of the last ice sheet, a concept now generally out of favour and contrary to terrestrial evidence and current geophysical modelling.

Gornitz, V., Lebedeff, S. and Hansen, J., 1982. Global sea level trend in the past century. Science, vol. 215, pp. 1611-1614.

Tide gauge records from around the globe are analysed in order to determine the algebraic sign of recent sea level changes. The authors claim to see evidence for a recent rise in sea level on the order of 12 cm/century. This rise is suggested to be due to thermal expansion of the upper layers of the ocean since the rise correlates with the trend of global surface air temperature. This result suggests that not all presently observed relative sea level change is due to residual postglacial deformation.

Peltier, W.R. and Andrews, J.T., 1976. Glacial-isostatic adjustment-I. The forward problem. Geophysical Journal of the Royal Astronomical Society, vol. 46, pp. 605-646.

This paper applies Peltier's (1974) Green's function approach to analyse the postglacial rebound record on a global scale. The main use of this paper at present is its definition of a global ice reconstruction averaged over grids 5 degrees on a side and averaged over 1000 year intervals.

Quinlan, G. and Beaumont, C., 1981. A comparison of observed and theoretical postglacial relative sea level in Atlantic Canada. Canadian Journal of Earth Sciences, vol. 18, pp. 1146-1163.

By modifying the spatial resolution of the Farrell and Clark (1976) model, the authors establish that the relative sea level record within Atlantic Canada is a sensitive function of the deglaciation history of the area. Two extreme models of deglaciation are tested and shown to have relative sea level consequences that bound the observed record. The relative sea level record is shown to be separable into isostatic and eustatic components by use of this theoretical model but not by use of any observational data. For formerly glaciated areas, the relative sea level record implies a strain rate that is very close to the strain rate implied by the isostatic uplift component. This is not so for areas distant from glaciation.

Quinlan, G. and Beaumont, C., 1982. The deglaciation of Atlantic Canada as reconstructed from the postglacial relative sea level record. Canadian Journal of Earth Sciences, vol. 19, pp. 2232-2246.

Following on the results of Quinlan and Beaumont (1981), the authors apply a systematic searching technique to refine their two extreme models of deglaciation for Atlantic Canada. An intermediate ice reconstruction is proposed that accounts for most of the observed relative sea level record over the last 13,000 years. This model can be used to estimate features of the rebound record that are not amenable to direct observation.

Shepherd, F.P. and Curray, J.R., 1967. Carbon-14 determination of sea level changes in stable areas. Progress in Oceanography, vol. 4, pp. 283-291.

This is a classic paper determining the so-called eustatic sea level variation by analysis of the relative sea level record of sites remote from centres of continental glaciation. The assumption is that such areas are free from isostatic deformation and so record only the change in water volume in the oceans. This assumption is incorrect as discussed in the text of this report and so this paper should be regarded with scepticism despite its wide use in the published literature.

Stein, S., Sleep, N., Geller, R.J., Wang, S.C. and Kroeger, G.C., 1979. Earthquakes along the passive margin of eastern Canada. Geophysical Research Letters, vol. 6, pp. 537-540.

The focal mechanisms of 7 earthquakes along the eastern margin

of Canada are deduced from seismic records of the events. The focal mechanisms are claimed to fall into two classes according to whether the epicentre lies landward or seaward of the 1,000 m bathymetric contour. Those occurring landward involve normal faulting while those occurring seaward involve reverse faulting. This pattern is analysed in terms of a simple flexural model of deglaciation and shown to be consistent with the behaviour of a collapsing peripheral bulge beneath the seaward quakes and a rebounding region beneath the landward quakes. The difficulty with the paper is the simplicity of the flexural model and the poor statistics of the focal mechanism analyses. Quinlan (1984) has questioned some of these results.

Vanicek, P., 1976. Pattern of recent crustal movements in Maritime Canada. Canadian Journal of Earth Sciences, vol. 13, pp. 661-667.

Linear vertical movements are computed from sea level change obtained from tide gauge records and relevelling the First Order level network. They indicate a west to northwest trend of fast subsidence across the eastern end of Bay of Fundy, and a possible area of uplift in northeastern New Brunswick. The maximum subsidence is ca. 35 cm in ca. 60 years.

Vanicek, P. and Nagy, D., 1981. On the compiliation of the map of contemporary vertical crustal movements in Canada. Tectonophysics, vol. 71, pp. 75-86.

A map of vertical movements in Canada is constructed from relevelling data and tide gauge observations. Much of the country is too sparsely covered by such observations to make any legitimate conclusions. The Yukon area is uplifting at a rate of 150-200 cm/century; much of B.C. is uplifting at a rate of 20-60 cm/century; the Praries are subsiding at a rate of 20-200 cm/century; the Great Lakes region is uplifting at a rate of up to 60 cm/century; Atlantic Canada is uplifting in the western parts at a rate of up to 100 cm/century and subsiding in the eastern parts at a rate of up to 80 cm/century.

Walcott, R.I., 1972. Past sea levels, eustasy and deformation of the Earth. Quaternary Research, vol. 2, pp. 1-14.

This paper is an early attempt to model the global relative sea level consequences of deglaciation and has been superseded by more realistic models of Peltier and Farrell and Clark. It is important primarily for its definition of eustatic sea level changes as the ocean-wide average change in mean sea level and its recognition that this average change is not uniform everywhere.

Walcott, R.I., 1972. Late Quaternary vertical movements in Eastern North America: quantitative evidence of glacio-isostatic rebound. Reviews of Geophysics and Space Physics, vol. 10, pp. 849-884.

This paper is an early attempt to model the postglacial uplift of eastern Canada. The model employed is not as sophisticated as those of Peltier and Andrews (1976) or Quinlan and Beaumont (1981, 1982) but the paper is still useful because of its compilation of observational data. Until the very recent work of Wolf (1985), this was the only attempt to look at shoreline tilt data in terms of lithospheric thickness and deformation properties.

Wolf, D., 1985. A new estimate of lithospheric thickness based on a re-interpretation of uplift data from Pleistocene Lake Algonquin. Canadian Journal of Earth Sciences, vol. 22, pp. 768-773.

Strandline tilt measurements from glacial Lake Algonquin in Ontario are used to estimate the thickness of the lithosphere. Wolf shows that the tilt data imply a lithospheric thickness of no more than 110 km. This value is significant for a study of rebound induced stress because the lithosphere is often modelled as an elastic plate in order to evaluate the regional stress field.

1.2 Strain Rate Due to Erosion

Ambrose, J.W., 1964. Exhumed paleoplains of the Precambrian shield of North America. American Journal of Earth Science, vol. 262, pp. 817-857.

An old classic paper which describes at length the possibility that much of the shield consists of ancient upland surfaces as old as early Proterozoic, subsequently buried and resurrected. In detail most of the evidence has been disproved, but the possibility remains.

Andrews, J.T., Jull, A.J.T., Dohahue, D.J., Short, S.K. and Osterman, L.E., 1985. Sedimentation rates in Baffin Island fiord cores from comparative radiocarbon dates. Canadian Journal of Earth Sciences, vol. 22, pp. 1827-1834.

Radiocarbon dates from two piston cores indicate sedimentation rates were highest 9 to 6.5 Ka BP while fiord glaciers were undergoing substantial retreat in Baffin Island. Sedimentation rates from the fiords vary from 0.5 cm/year to 0.02 cm/year. It is very difficult to express this in sediment yield terms, but it probably represents very low rates of erosion for the northeastern sector of the Laurentide ice sheet.

Bell, M. and Laine, E.P., 1985. Erosion of the Laurentide Region of North America by glacial and glaciofluvial processes. Quaternary Research, vol. 23, pp. 154-174.

This paper contains an examination of data from the continental

margins and ocean basins around North America to estimate the amount of material eroded from the area covered by the Laurentide ice sheet. A minimum estimate is 1.62 million cubic metres, or an average of 120 m of rock in a glacial age defined as 3 million years long. This is much higher than estimates based on terrestrial evidence of till thickness, and on river sediment loads. Erosion from Greenland and Antarctic ice sheets are probably much less than from periodic ice sheets like the Laurentide. Table 5 in the paper has data on chemical erosion rates for climates from temperate humid (35 t/km^2/year) to arid (3 t/km^2/year), averaging 16.7 for the Laurentide area. Table 6 is from Milliman and Meade (1983); modern suspended sediment yield. Shield areas are ca. 8 t/km^2/year, St. Lawrence valley is ca. 4 t/km^2/year, both much below the average of 19.4 t/km^2/year.

Bird, J.B., 1972. The denudational evolution of the Maritime Provinces, Canada. Revue de Geographie de Montreal, vol. XXVI, no. 4, pp. 421-432.

A descriptive account of the upland surfaces of maritime Canada which were usually thought to have been formed during Mesozoic and Cenozoic time. They are thought to have been formed by fluvial erosion, graded down to ancient sea levels and subsequently uplifted through isostatic response to the removal of mass. Bird suggests the surfaces may be as old as late Paleozoic in age, while the valleys and lowlands were excavated in Cenozoic time. This is based largely on the existence of sedimentary outliers of Mesozoic and early Cenozoic age found in scattered areas.

Chapman, C.A. and Rioux, R.L., 1958. Statistical study of topography, sheeting, and jointing in granite, Acadia National Park, Maine. American Journal of Science, vol. 256, pp. 111-127.

Field and laboratory evidence are used to show the relationship between topography and structure in a mountainous area of subaerial erosion by streams, prior to and after erosion by ice. They use SSO (statistical slope orientation) diagrams, and joint orientation in reconstructing preglacial topography. Sheeting generally represents preglacial denudation. Ice advance was oblique to the topographic symmetry plane and glacial erosion was adequate to transform the monoclinic pattern of joints to one of triclinic symmetry.

Clark, S.P. and Jaeger, E., 1969. Denudation rate in the Alps from geochronologic and heat flow data. American Journal Science, vol. 267, pp. 1143-1160.

Authors estimate a minimum erosion rate of 0.1 km/ma for denudation in the Alps.

Gilluly, J., 1964. Atlantic sediments, erosion rates, and evolution of the continential shelf: some speculations.

Geological Society America Bull., vol. 75, pp. 483-492.

The author suggests that an erosion rate of 0.01 km/ma is characteristic of the eastern United States. Note that this will result in little to no change in near surface temperatures during erosion.

Gordon, R.B., 1979. Denudation rate of central New England determined from estuarine sedimentation. American Journal of Science, vol. 279, pp. 632-642.

This paper compares the sediment yield from several rivers flowing into Long Island Sound, including the Connecticut River, with the volume of sediments revealed by seismic survey of the Sound. Both sources agree that over the last 8 thousand years sediment yield has been ca. 4,200 million kg/year, involving a denudation rate of ca. 10 tonnes/km^2/year. This low rate is ascribed to the stablised land surfaces of resistant bedrock and lodgement tills. Sediments from glacial Lake Hitchhock, 10,700 to 13,700 years old, which had a sedimentation rate 3 times that of Long Island, are the major source of present stream loads. Streams are markedly underfit since there was a large reduction in flow about 10,000 to 8,000 years ago.

Gravenor, C.P., 1975. Erosion by continental ice sheets. American Journal of Science, vol. 275B, pp. 594-604.

This contains a critical examination of White (1972). From southermost erratic indicators, it is known that Canadian Shield rocks were exposed prior to the first Cenozoic glaciation in North America. Erosion was most active near the borders of the limits of ice advance, and involved little of the shield. Even the GreatLakes basins existed prior to glaciation.

Gregor, B., 1970. Denudation of the continents. Nature. vol. 228, pp. 273-275.

Prehuman and modern denudation rates are calculated on the ratio between the transport rate of dissolved sodium in rivers and the sodium leached from a unit mass of source rock. The prehuman rate is thought to have been in the order of 10,500 tonnes/year, while modern rates are thought to be more like 24,000 tonnes/year.

Laine, E.P., 1980. New evidence from beneath the western North Atlantic for the depth of glacial erosion in Greenland and North America. Quaternary Research, vol. 14, pp. 188-198.

Laine determined the volume of glacial-age turbidites and margin deposits in the western North Atlantic, and estimated source areas. He calculated that 55-95 m of rock were eroded off the northeastern part of North America and off southern Greenland. The major weakness in this paper is its failure to account for sediments lost to the Gulf of Mexico. Bell and Laine (1985)

address this problem and derive somewhat higher estimates for erosion.

Matthews, W.H., 1975. Cenozoic erosion and erosion surfaces of eastern North America. American Journal of Science, vol. 275B, pp. 818-824.

Cenozoic sediments in the Western North Atlantic amount to about 1000 km^3/km of the 3,000 km coast from Georgia to Newfoundland. This represents $400^3/km$ erosion from a hinterland of ca. 1.9 million km^2. This area is widest to the north where the volume of sediment is least. In the north 0.3 km^3/km^2 of erosion occurred in 60 million years, or ca. 400 m of denudation. In the south, values are ca. 5 times higher. A major problem is interpreting the Gulf of St. Lawrence, the volume of which is equal to all of the offshore sediments nearby. It may have been differentially faulted in Neogene times or later, and Matthews emphasizes the need to search for late differential land movements in the Maritime provinces and Newfoundland to account for the anomaly.

Milliman, J.D. and Meade, R.H., 1983. World-wide delivery of river sediment to the oceans. Journal of Geology, vol. 91, pp. 1-21.

The total suspended sediment and bedload delivered to the world's oceans is about 15 x 10^9 tonnes/year, more than 70% of which comes from south Asia and the Pacific Rim. World sediment yield is 116 tonnes/km^2/year, while for the Canadian Shield the yield is <10 tonnes/km^2/year, and for the St. Lawrence and New England the rate was between 10 and 50 tonnes/km^2/year.

Plumb, R., Engelder, T. and Sbar, M., 1984. Near-surface in situ stress - 2. A comparison with stress directions inferred from earthquakes, joints, topography, near Blue Mountain Lake, New York. Journal of Geophysical Research, vol. 89, B 11, pp. 9333-9349.

At 11 outcrops within 100 km of Blue Mountain Lake, NY, strain relaxation was measured during overcoring. Maximum expansion was usually parallel with contemporary tectonic stress field and aligned with topographic contours. Feedback between contemporary tectonic stress field, which is east-northeast in the northeastern US, and process of jointing during the development of local topography was noted. Both were controlled by local structures, a reflection of contemporary tectonic stress, but not a direct measure of it. Introduced the 'GCS' hypothesis (Geomorphic controlled stress) for near-surface stresses associated with relaxion on weathering and erosion of local topography.

Reed, L.A., 1971. Hydrology and sedimentation of Corey Creek and Elk Run Basins, north central Pennsylvania. United States Geological Survey, Water Supply Paper, 1532-E, 27pp.

The basins lie in the glaciated part of the folded Appalachian Plateau. They are >1,300 feet above sea level, and a 13 year sediment yield record give means of 126 and 137 tonnes/mile^2/year.

Stephenson, R. and Lambeck, K., 1985. The erosion-isostatic rebound models for uplift; an application to south-eastern Australia. Geophysical Journal of the Royal Astronomical Society, vol. 82, pp.31-55.

Authors discuss erosionally induced uplift in south-eastern Australia that has occurred during the Cenozoic.

Sugden, D.E., 1978. Glacial erosion by the Laurentide ice sheet. Journal of Glaciology, vol. 20, pp. 367-391.

This classic paper is an analysis of landscapes of glacial erosion formed by the Laurentide ice sheet at its maximum, related to a model of basal ice temperature, erosive stress, bed topography and geology. It points to many areas where little or no erosion is evident, especially north of 70°N, associated with cold-based ice. Erosion was generally inversely proportional to rock permeability. He uses lake basin density as an index of erosion, noting a high-density of occurrence forming a ring between periphery and centre, possibly where basal freezing causes excavation. The Laurentide ice sheet may have existed at its maximum for a long period of time at some stage, creating equilibrium bed-landforms.

White, W.A., 1972. Deep erosion by continental ice sheets. Geological Society of America. Bulletin, vol. 83, pp. 1037-1056.

Four main observations are used to argue that ice sheets removed stratigraphic cover from Precambrian shields: 1. similar shape, extent of ice sheets and shields; 2. arcs of exhumation exist around the shields; 3. exhumed pre-Paleozoic terrain around the periphery slopes outwards, while inner shield slopes in and has no bornhardts; 4. hierarchies of basins are carved in the former ice-covered area e.g. Hudson Bay to Great Lakes to Finger Lakes.

Williams, K.F. and Reed, L.A., 1972. Appraisal of stream sedimentation in the Susquehanna Basin. United States Geological Survey, Water Supply Paper, 1532-F, 24 pp.

This includes values of sediment yield from the Susquehanna River and several of its sub-basins. Values range from 40 to 440 tonnes/mile^2/year, with geological control on yield important in the Valley and Ridge province of the Appalachians. In particular, basins with >25% limestone were typified by very low yields.

1.3 Strain Rate Due to Tectonic Stresses

Brown, L.D., 1978. Recent vertical movement along the east coast of the United States. Tectonophysics, vol. 44, pp. 205-231.

Results of precise levelling experiments are compared with secular trends from tide gauges along the east coast of the United States. There is enough lack of agreement between the results of the two techniques to suggest that one or both sets of measurements contain non-tectonic contamination. Strong correlations exist in the levelling results between apparent movements and tectonic and geopmorphic features on a regional scale. Each of the Connecticut Synclinorium and Cape Fear Arch are associated with changes in the uplift profile. There seems to be a consistent increase in rate of uplift from ca. 3 mm/yr in Maine to ca. 17 mm/yr in Florida with pronounced changes across the above mentioned features. Until the discrepancy with tide gauge results is clarified it is difficult to have much confidence in the overall north-south trend. It is also difficult, however, to see why systematic errors in measurement should result in the correlation of uplift rates with geological structure. It seems reasonable to assume that the correlation with structure is real and represents an interaction between tectonic stress and pre-existing structural weaknesses.

Castle, R.O., Church, J.P. and Elliot, M.R., 1976. Aseismic Uplift in Southern California. Science, vol. 192, pp. 251-253.

Geodetic data from 1960 onward are analysed and shown to indicate uplift of between 15 and 25 cm over an area of 12,000 square km centred on the intersection of the Garlock and San Andreas fault systems. Deformation in this area of the fault system has been proceeding episodically rather than at a constant rate over this interval and is most logically interpreted in terms of buildup of elastic stress in the crust because of locking of the fault system in the area. Jackson and Lee (1979) have, however, questioned whether the uplift is in fact real, suggesting that it may be due to systematic error in the geodetic measurements.

Mckay, D.A., Williams, J.B., Bowlby, J.R. and Grass, J.D., 1985. Miramichi epicentral area - in situ stress pilot project. Ontario Hydro Research Division, Report No. 85-185-K.

Five or six borings in Miramichi region epicentral area, 2.25 years after major earthquake, indicate principal secondary stress in the horizontal plane has a NE(055) to E(095) orientation. Not a pure thrust fault as suggested from seismic records. Records of rock bursts and pop-ups during drilling.

2. Development and Rejuvenation of Faults and Fractures Due to Glacial Loading, Erosion and Tectonic Stress.

This section of the annotated bibliography consists of papers which refer to postglacial faults or tectonics in eastern Canada and the US and in Fennoscandia. Several papers for northern Canada are also included which contain detailed surveys of Glacial Lake shorelines which contain no evidence of faulting. The annotation usually deals with the specific information which the reference contains concerning faulting and is not a comprehensive abstract of the whole paper.

Originally this section was to have two separate lists, one with references to new faults, the other with references to rejuvenation of earlier faults. This proved, however, not to be a feasible separation. Most authors who are cautious in the interpretation of fresh faults in bedrock indicate that they may be a rejuvenation of earlier faults, or coincide with older fault zones. Adams (1981) considered it probable that many postglacial faults are reactivated and suggests that differential loading resulting from different thicknesses of ice across a fault-line scarp, may result in stress concentrations that could form new faults or rejuvenate old faults at these locations. Any separation of the two categories of faults in bedrock may simply be a separation of cautious and incautious reports.

Adams, J., 1981. Postglacial faulting: a literature survey of occurrences in Eastern Canada and comparable glaciated areas. Atomic Energy of Canada Ltd. Technical Record TR-142, 63 pp.

Fifty-four references to postglacial faulting in >65 localities. Mostly small-displacement thrusts in a broad arc from Ontario to southern Newfoundland. Some association with slaty rocks. Some are reactivated old faults. Much of faulting thought to be 14 ka to 8 ka BP in response to crustal flexure caused by deglaciation.

Adams, J., 1982. Stress-relief buckles in the McFarland quarry, Ottawa. Canadian Journal of Earth Sciences, vol. 19, pp. 1883-1887

Six quarry-floor buckles formed following removal of 15 m near-horizontally-bedded limestone. Pop-ups, up to 180 m long, 6 m wide, 1.5 m high, oriented 120 - 150°, horizontal compression from NE - SW.

Andrews, D.E., 1980. Glacially thrust bedrock - an indication of late Wisconsin climate in western New York State. Geology, vol. 8, no. 2, pp. 97-101.

Report of very low angle/horizontal thrust in shale bedrock associated with tills; 45 m long, 6 m thick unit, thrust from

east to west. Not isostatic nor tectonic, but related to thermal regime of over-riding ice mass. Clearly different from other reverse faults associated with neotectonics.

Barnett, D.M. and Peterson, J.A., 1964. The significance of Glacial Lake Naskaupi 2 in the deglaciation of Labrador-Ungava. Canadian Geographer, vol. 8, pp. 173-181.

Despite extensive levelling of glacial lake Nascaupi 2 shorelines which stretch >250 km N - S, and 50 km E - W, and have a gradient upwarped 0.44 m/km to SW from 395 m asl at Mount Pyramid to 430 m at Whitegull Lake, the authors observed no irregularities due to faulting.

Basham, P.W., Adams, J. and Anglin, F.M., 1983. Earthquake source models are discussed for estimating seismic risk on the eastern Canadian continental margin. Fourth Canadian Conference on Earthquake Engineering, Vancouver, B.C., June 15-17, 1983.

Alternate seismic source models are discussed for estimating seismic risk in eastern Canada. These are based primarily on assumptions regarding the statistical nature of earthquakes within any given area. Without a better understanding of the ultimate tectonic cause of earthquakes within the region, these models should be considered as speculative.

Basham, P.W. and Adams, J., 1984. The Miramichi, New Brunswick earthquakes: near-surface thrust faulting in the northern Appalachians. Geoscience Canada, vol. 11, no. 3, pp. 115-121.

Report of magnitude 5.7 earthquake on Jan. 9, 1982 and subsequent fieldwork in Miramichi Highlands looking for new faults. In SE corner of aftershock zone glacier-smoothed bedrock was found freshly displaced by thrusting along joint plane, 3 m long, 25 mm offset, west side up, oriented 005°, dip to west. Also found, was stress-relief buckle formed overnight; slab of diorite, 3 m long, 1 m wide, buckled up 55 mm, since increased to 80 mm, cracked along trend 010. Suggests NB subject to horizontal compression, approximately in an E-W direction.

Bath, M., 1978. Energy and Tectonics of Fennoscandian earthquakes. Tectonophysics, vol. 50, no. 1, pp. T9-17.

Energy-time release curves calculated for Fennoscandian earthquakes shows a sharp break in activity at 1910. The author claims that this is a global phenomenon, suggesting plate motions or other tectonic causes for faulting in Holocene.

Bjerhammar, A., 1977. The gravity field in Fennoscandia and postglacial crustal movements. KBS Teknisk Rapport 17, 92 pp.

Attempt to assess whether present uplift is tectonic or glacio-isostatic. Important because magnitude of uplift similar to displacement at San Andreas. If tectonic, seismically a risky

area for nuclear waste disposal. Struggles with problem of eustasy and apparent as against true uplift of crust. No significant difference in eustatic change over range of sites from Sweden to Britain. Examined uplift data from Morner and Tooley, both of whom thought tectonic factors were present after 5 ka BP, and found <1% probability that the 8 ka and present rates of uplift have different origins. Justified to conclude that glacio-isostatic uplift has not ceased and is main cause of present vertical movements in Scandinavia. Very small tectonic movements may exist, but not evident in present data.

Block, J.W., Clement, R.C., Lew, L.R. and de Boer, J., 1979. Recent thrust faulting in southeastern Connecticut. Geology, vol. 7, pp. 79-82

Boreholes by highway offset by SE-directed thrusting by 10 to 280 mm since 1970, along pre-existing faults. One moving at 2.8 mm/year. One hundred km to NE, faults in sandstones strike 050°, upthrust to NW 12 to 18 mm. This is one of several articles which from a wide scatter of observations combine to suggest active compression across New England.

Broecker, W.S., 1966. Glacial rebound and the deformation of shorelines of proglacial lakes. Journal of Geophysical Research, vol. 71, pp. 4777-4783.

In this classic analysis of deformation of Lake Algonquin shorelines, relationship between uplift and distance to ice margin is examined. No irregularities due to faulting are noted.

Brown, L.D., Reilinger, R.E. and Citron, G.P., 1980. Recent vertical crustal movements in the US: evidence from precise levelling. in 'Earth rheology, isostasy and eustasy', edited by N-A. Morner, Wiley and Sons, pp. 389-405.

Precise geodetic levelling reveals uplifts are as large in east, N. Carolina, as in west. Up to 20 cm change in 30 years at high elevations, west of Brevard Fault, Tenn. Over 2 cm/year in Florida. Not smooth curves but some steep sections suggesting faults or zones of concentrated strain. Suggests east is more tectonically active than usually realized. However refer to comments on Brown (1978) regarding 'quality' of measurements used.

Chalmers, R., 1897. Report on the surface geology and auriferous deposits of south-eastern Quebec. Geological Survey of Canada, Annual Report X, part J, 160 pp.

Postglacial faults in slates from Sherbrooke to St.Georges. All thrust, strike about 050°, south side up. Length up to several hundreds of metres, displacement up to 2 m, though most just a few cm. Striations offset. Suggest tectonic compression from southeast.

Coates, D.F., 1964. Some cases of residual stress effects in engineering work. in 'State of stress in the earth's crust', edited by W.R. Judd, Elsevier, NY, pp. 679-688.

Removed >15 m limestone near Kingston, Ont., quarry floor buckled, about 100 m long, >2 m high, orientation not mentioned. Horizontal compressive stresses inferred.

Cushing, H.P., Fairchild, H.L., Ruedemann, R. and Smyth, C.H., 1910. Geology of the Thousand Islands region. New York State Museum Bulletin 145, 182 pp.

Six postglacial folds or pop-ups. Up to 40 m long, about 4 m high, oriented about 330°, indicate compression from northeast, authors consider that these features may be due to postglacial (isostatic?) warping.

Decker, C.E., 1915. Recent crustal movements in the eastern part of the Great Lakes region. Illinois Academy of Science Transactions, vol. 8, pp. 97-100.

From Cleveland east, shales deformed. Faults and folds deform overlying glacial sediments and one uplifts terrace by almost 2 m at thrust. No orientation data, but clearly compressive.

Feyling-Hanssen, R.F., 1966. Geologiska observationer i Sandnesomradet. Norges Geol. Undersokn 242, pp. 26-43.

Reports of faulting after deposition of Wurm till south of Stavanger, in the Western Norwegian structural zone.

Gerber, R.G. and Rand, J.R., 1978. Late Pleistocene deformations of bedrock and till, Sears Island, Searsport, Maine. Geological Society of America, Abstracts with Programs, vol. 10, no. 2, pp. 43-44.

At proposed nuclear plant site, till cleared to reveal thrust fault oriented 050°, length unknown, offset 2.5 cm. Attributed to ice loading.

Goldthwaite, J.W., 1924. Physiography of Nova Scotia. Geological Survey of Canada Memoir 140, 179 pp.

Three locations of faulting of striated slates, at Caledonia Corner, Halifax and Kejimkujik. Oriented 050°, thrust offset up to 19 cm, up to north.

Goodacre, A.K. and Hasegawa, H.S., 1980. Gravitationally induced stresses at structural boundaries. Canadian Journal of Earth Sciences, vol. 17, pp. 1286-1291.

A correlation is proposed between the occurrence of paired positive and negative gravity anomalies and seismic activity within cratonic areas. The gravity anomalies are due to

juxtaposition of crustal blocks of differing densities. This density contrast sets up elastic stress in the lithosphere which acts to trigger release of seismic energy. The model is tested against observed seismic patterns in the lower St. Lawrence Valley and found to be spatially consistent. The generality of this model seems doubtful, however, because of the lack of significant levels of seismicity in the vicinity of other major structural boundaries such as exist between geological provinces. The presence of gravity anomalies across these province boundaries attests to the existence of similar stress levels. LeBlanc and Buchbinder (1977) correlate the seismicity of this region more strongly with the Charlevoix impact structure than with the Appalachian structural front (Logan's Line) as in this paper.

Grant, D.R., 1975. Surficial geology of northern Cape Breton Island. Geological Survey of Canada, Report of Activities, part A, Paper 75-1A, pp. 407-408.

Shoreline platform horizontal at 6 m north of Aspy Fault zone. South of it is 12 m high. Faulting postdates last interglacial.

Grant, D.R., 1980a. Quaternary stratigraphy of southwestern Nova Scotia: glacial events and sea-level changes. Geological Association of Canada, Guidebook to trip 9, 63 pp.

Salmon River, glacially-smoothed slate, many small faults total throw of 1 m, postglacial.

Grant, D.R., 1980b. Quaternary sea-level change in Atlantic Canada as an indication of crustal delevelling. in 'Earth rheology, isostasy and eustasy', edited by N-A. Morner, Wiley, pp. 201-214.

Shoreline platform of interglacial age tilted to north, faulted up at Aspy Fault and Long Range fault. Throw 20 m to 1 m.

Grice, R.H., 1972. Engineering geology of Montreal. 24th International Geological Congress Guidebook, excursion B-18, 15 pp.

Two slices limestone thrust 1.5 to 3 m over till. May be superficial ice thrusting.

Harrison, D.A., 1963. The tilt of the abandoned lake shorelines in the Wabush-Shabogamo Lake area, Labrador. McGill Sub-Arctic Research Papers 15, pp. 15-22.

Uniform tilt of glacial lakes Wapussakato 2 and 3 demonstrated and no instances of irregularities due to faulting are noted.

Hasegawa, H.S., Adams, J. and Yamazaki, K., 1985. Upper crustal stresses and vertical stress migration in eastern Canada.

Journal of Geophysical Research, vol. 90, pp. 3637-3648

In situ stress measurements and earthquake fault plane solutions in the upper 5 - 20 km of the crust suggest the maximum horizontal stress exceeds vertical stress. Maximum compressive stress is primarily ENE and probably related to propagation of stress through the lithosphere from the Mid-Atlantic Ridge. Postglacial rebound stress is estimated to be at least an order of magnitude less significant.

Henkel, H., Hult, K. and Eriksson, L., 1983. Neotectonics in northern Sweden - geophysical investigations. KBS Teknisk Rapport TR 83-57, 64 pp.

Geophysical investigations of faults in Swedish Lapland, including 150 km long Parvie fault show clear identification of fault characteristics from aerial sensors, but do not confirm the age, magnitude or current activity of the faults.

Hickman, S.H., Healy, J.H., Zoback, M.D., 1985. In situ stress, natural fracture distribution and borehole elongation in the Auburn geothermal well. Auburn, New York, Journal of Geophysical Research, vol. 90, pp. 5497-5512.

Hydraulic fracturing tests in the 1.6 km deep geothermal well at Auburn, N.Y. indicate stress orientation in an ENE direction throughout the length of the well section. Distinct natural fractures persist throughout the entire depth of the well. Fracture patterns in the lower half of the sedimentary section of the well strike E-W. The origin of this fracture pattern is unclear as it parallels both the current maximum compressive stress and also the paleostress direction inferred for the late Paleozoic on the basis of Appalachian Plateau fold axes. As such, the fractures could be either relict or recent.

Hilaire-Marcel, C., 1980. Multiple-component postglacial emergence, eastern Hudson Bay, Canada. in 'Earth rheology, isostasy and eustasy', edited by N-A. Morner, Wiley, pp. 215-230.

Emergence rate interpreted as oscillatory isostatic response with wavelength of about 2 ka. Emergence clearly a discontinuous phenomenon with succession of standstills and rapid drops.

Hobbs, W.H., 1907. Earthquakes. Appleton and Co. NY, 336 pp.

Review of known postglacial faults. Vertical offsets of 2 cm, hingeline of deformation in old lake shorelines noted from Michigan to Ohio.

Hobbs, W.H., 1911. The late glacial and post glacial uplift of the Michigan Basin. Michigan Geological and Biological Survey, Publication 5, Geological Series 3, 45 pp.

Wisconsin quarry with striated limestones offset by fault up to 3 cm on joints 015 to 083° in orientation.

Husebye, E.S., Bungum, H., Fyen, J. and Gjoystal, H., 1978. Earthquake activity in Fennoscandia between 1497 and 1975 and intraplate tectonics. Norsk Geol. Tidskr. 58, pp. 51-68.

Collection of seismicity maps on macroseismic information (1497-1950) and instrumental information since 1950 show fair agreement. Very difficult to separate very few tectonic events from quarry blasts, etc.; 55-80 percent quakes are shallow, <20 km depth; 400 a recurrence interval for 6.5 magnitude quake.

Isachsen, Y.W. and Wold, R.J., 1977. Geodetic, geological and geophysical evidence for Holocene vertical movements in the Adirondack region, New York. Geological Society of America, Abstracts with Programs, vol. 9, no. 3, p. 279.

Postglacial faults along vertical joints cut striated bedrock. Throw of 10 mm, oriented 340°, up to east.

Isachsen, Y.W., Geraghty, E.P. and Wright, S.F., 1978. Investigation of Holocene deformation in the Adirondack Mountain Dome. Geological Society of America, Abstracts with Programs, vol. 10, no. 2, p. 49.

Some offsets up to 3 mm may be result of blasting, ice wedging or tectonic effects.

Karrow, P.F., 1963. Pleistocene geology of the Hamilton-Galt area. Ontario Department of Mines, Geological Report 16, 68 pp.

Thrust fault near Burlington oriented 000°, offset vertical by 50 cm up to east. 1949 report of pop-up near Westover, 100 to 200 m long, 1.2 m high, dammed stream and lifted trees and small bridge.

Lagerback, R. and Henkel, H., 1977. Studies of neotectonic activities in central and northern Sweden, review of aerial photographs and geophysical interpretation of recent faults. KBS Teknisk Rapport TR 19, 29 pp.

Late glacial faults described from N. Sweden identified from air photos. Morphologically conspicuous, marked by step in till cover, over 100 km long west of Kiruna (Parvie Fault). All faults are in Precambrian rocks and oriented NE to SW, often parallel to structure, may coincide with older fault zones; 150 km long. 30 m vertical offset, up some to E, some to W. Some connection with recent seismic pattern but isostasy inferred as cause.

Lagerback, R. and Witschard, F., 1983. Neotectonics in northern Sweden - geological investigations. KBS Teknisk Rapport, TR

83-58, 58 pp.

Photogrammetric measurements of Norbotten faults give apparent displacements up to 30 m. Parvie Fault is longest, 150 km, oriented 050°, and up to SE with maximum throw of 13 m. Laive-Suijavaara fault has displacement of 26 m.

Lagerlund, E., 1977. The stratigraphy and neotectonism in southern Sweden. Boreas, vol. 6, pp. 159-166.

Till stratigraphy and strong relief imply postglacial movements of up to 100 m for the horst of Kullen Hill in the Fennoscandian border zone.

Lawson, A.C., 1911. On some post-glacial faults near Banning, Ontario. Seismological Society of America Bulletin 1, pp. 159-166.

Postglacial faults offset striated slates. Oriented 080, thrust up to north; 5 to 20 m long, 2 to 8 cm displacement. May be connected with volume change as ice load released.

LeBlanc, G. and Buchbinder, G., 1977. Second microearthquake survey of the St. Lawrence Valley near La Malbaie, Quebec. Canadian Journal of Earth Sciences, vol. 14, pp. 2778-2789.

A microseismicity survey near La Malbaie located 34 microearthquakes accurately. The epicentres were all within the Precambrian Grenville Province and none within the adjacent Ordovician sediments lying south of Logan's Line (Appalachian structural front). Futhermore there is a distinct clustering of hypocentres within the boundary of the Charlevoix impact structure rather than spread uniformly along Logan's Line. Although the authors suggest a possible connection with Logan's Line, they quite reasonably point out the importance of the impact structure in determining the exact location of the seismicity.

Lee, S.M., 1965. Inussuaq - Pointe Normond area, New Quebec. Quebec Department of Natural Resources, Geological Report 119, 134 pp.

Near mouth of Kongut River, shore of Hudson Bay, faults form 3 to 6 m scarps with fresh-looking slickensides. Postglacial origin inferred.

Liberty, B.A., 1969. Paleozoic geology of the Lake Simcoe area, Ontario. Geological Survey of Canada Memoir 355, 201 pp.

Minor faults, one up to 0.8 km long, 10 cm to 2 m displacement. Normal faults not modified by glacial abrasion.

Lo, K.Y., 1978. Regional distribution of 'in situ' horizontal stresses in rocks of southern Ontario. Canadian Geotechnical

Journal, vol. 15, pp. 371-381.

Toronto: 2 postglacial faults, other indicators such as buckles and pop-ups that high horizontal stresses occur within 30 km wide arc around western end of Lake Ontario. Probably tectonic rather than isostatic.

Loken, O.H., 1962. The late-glacial and postglacial emergence of northernmost Labrador. Geographical Bulletin 17, pp. 23-56.

Three raised strandlines between 28 and 56 m asl, tilt up to SSW. 20 metre asl strandline horizontal. Marine limits around 56 m maximum. Strandline-3, about 30 m asl dated about 9 ka BP.

Loomis, F.B., 1921. Postglacial faulting about Mount Toby, Massachusetts. Geological Society of America Bulletin 32, pp. 75-80.

Postglacial lake shoreline drops >25 m across fault trending 350 to 045°, down to SW. Other offset shorelines apparent below about the 110 m asl bench.

Lundqvist, J. and Lagerback, R., 1976. The Parvie Fault: a late-glacial fault in the Precambrian of Swedish Lapland. Geologiska Foreningens Stockholm Forhandlinger 98, pp. 45-51.

One hundred and fifty km long fault, downthrow of dip-slip type, about 10 m displacement, cuts off eskers. More than 10 others to the SE.

Matthew, G.F., 1894. Post-glacial faults at Saint John NB. American Journal of Science, vol. 148, pp. 501-503

Faults at 5 locations in city. Steps displace striations, oriented 050°, upthrown to SE from 50 mm to 12 cm. Reverse faulting, suggest thrusting from SE.

Morner, N-A., 1977. Past and present uplift in Sweden: glacial isostasy, tectonism and bedrock influence. Geol. Forenning, Stockholm Forhandlingar 99, pp. 48-54

Identifies 600 X 30 km Precambrian Hyperite zone as major geodynamic boundary with past and present uplift affected by old faults and large structures. Irregularities in paleo-shoreline elevation from detailed levelling correlate with structures and gravity anomalies. Strong negative anomalies in trench-like zones of postglacial faulting. Uplift composed of two factors: glacio-isostasy died out 2 to 3 ka BP now replaced by tectonic uplift of unknown mechanism.

Morner, N-A., 1977b. Rorelser och instabilitet i den Svenska berggrunden. KBS Teknisk Rapport TR 18, 37 pp (English summary included).

Swedish bedrock unstable. Irregularities in uplift all related to major faults and joints. Faulting frequent during deglaciation. Small faults, up to 2 m, independent of zones of weakness, while larger ones not. Isostatic uplift died out 2 ka BP, now neotectonic.

Morner, N-A., 1978. Faulting, fracturing and seismicity as functions of glacio-isostasy in Fennoscandia. Geology, vol. 6, pp. 41-45.

Proposed that most rapid rate of uplift occurred around time of deglaciation, thus most faulting dates from that time which is time-transgressive in space.

Morner, N-A., 1979. Activities of the INQUA Neotectonics Commission. INQUA Neotectonics Commission Bulletin no. 2, 7 pp.

At Poste-de-la-Baleine, N. Quebec, offset striations with tens of cm uplift. Numerous examples.

Morner, N-A., 1982. Nuclear power on unstable ground. in 'Predictive Geology, with emphasis on nuclear waste disposal.' edited by G. de Marsily and D.F. Merriam, Pergamon, pp. 83-99

Fennoscandian shield not stable. 'Double' uplift in postglacial, one exponential, reflecting adjustments in low-viscosity asthenosphere, second linear representing mesospheric motions. Shape of shield has controlled all uplifts in last 22 ma, main movement concentrated in main seismic belt. Present uplift corresponds to higher viscosity than earlier. Seismic energy release in Sweden changed drastically in 1910 during major geomagnetic shift related to slow earth rotation. Horizontal rebound features may occur at depths of about 500 m. In Sterno area selected for disposal, 5 to 6 m faulting evident in early Holocene along block boundaries. Differential tilting indicated by repeated levelling.

Newman, W.A., 1979. The possibility of Pleistocene - Holocene movement along the Oak Bay fault on the Maine - New Brunswick border. Maine Geological Survey Open File 79-20, 7 pp.

Looks like a major fresh fault but Newman found no evidence for recent movement.

Oliver, J., Johnson, T. and Dorman, J., 1970. Postglacial faulting and seismicity in New York and Quebec. Canadian Journal of Earth Sciences, vol. 7, pp. 579-590

Eleven new sites of faulting identified. Belt from Hudson, to Lake Champlain to along St. Lawrence with faults of few cm, most up towards south or east. Distribution does not correlate with seismic patterns, may be glacio-isostatic or tectonic.

Quinlan, G., 1984. Postglacial rebound and the focal mechanisms of eastern Canadian earthquakes. Canadian Journal of Earth Sciences, vol. 21, pp. 1018-1023.

This is essentially a re-evaluation of the results of Stein et al (1979) in which the author calculates the stress field expected from a realistic model of postglacial rebound. He shows that the stress level expected from rebound is on the order of 100 bars but that such stress cannot determine the nature of faulting and can at best act as a trigger for pre-existing stress fields having their origin in other tectonic processes. If the pattern of focal mechanisms suggested by Stein et al. (1979) is real, then there must be stress-generating processes acting at passive continental margins to produce this pattern.

Ramberg, I., 1975. Gravity interpretation of the Oslo graben and associated igneous rocks. Norges Geol. Undersokn 325, pp. 1-194

Major boundary of faulting occurs for 3 km along south part of fiord, plus minor faults throughout graben, still active (site of 1904 earthquake). Some of faulting thought to be recent.

Rast, N., Burke, K.B.S. and Rast, D.E., 1979. The earthquakes of Atlantic Canada and their relationship to structure. Geoscience Canada, vol. 6, pp. 173-179.

Oak Bay Fault still site of earthquakes, though no evidence of active fault features. Earthquakes may be due to cooling of magma bodies rather than glacio-isostasy.

Sanford, B.V., Thompson, F.J. and McFall, G.H., 1985. Plate tectonics - a possible controlling mechanism in the development of hydrocarbon traps in southwestern Ontario. Bulletin of Canadian Petroleum Geology, vol. 33, pp. 52-71.

Detailed isopachs and facies analysis of Paleozoic rocks from southwestern Ontario are presented in order to outline trends of block faulting and rotation apparently coincident with sediment deposition. The authors relate this behaviour to propagation of tectonic stress through the lithosphere from the orogenic belts that ringed the continent during Paleozoic times. The correlation of seismic activity with some of these fault blocks suggests that current prevailing stress patterns in the North American lithosphere are continuing to produce rotation of the blocks. The validity of this argument depends to a large extent on the validity of the authors' identification of blocks and their bounding faults and fractures. The paper does not identify the source of the isopach data so that it is difficult to see how much control exists on these patterns. It is not entirely clear from the paper why some of the block boundaries are drawn where they are. Correlation of seismic activity with fault blocks may or may not be significant depending on whether the particular choice of block boundaries is meaningful. In summary, the ideas of this paper are not without merit but are difficult

to assess on the basis of supporting data presented.

Saull, V.A. and Williams, D.A., 1974. Evidence for recent deformation in the Montreal area. Canadian Journal of Earth Sciences, vol. 11, pp. 1621-1624.

Pop-ups in quarries, plus some indicators of recent wrench movement.

Sbar, M.L. and Sykes, L.R., 1973. Contemporary compressive stress and seismicity in eastern North America: an example of intra-plate tectonics. Geological Society of America Bulletin, vol. 84, 1861-1882.

Evidence from earthquake focal mechanisms, in situ stress measurements and observed deformation of geological and engineering structures all point to a maximum compressive stress that is oriented E to NE over much of North America. It is suggested that this orientation may be related to plate tectonic motions and flow in the underlying mantle. Several examples of pop-ups and high horizontal compressive stress on page 1869-70.

Sbar, M.L. and Sykes, L.B., 1977. Seismicity and lithospheric stress in New York and adjacent areas. Journal of Geophysical Research, vol. 82, pp. 5771-5786.

A dense coverage of seismic stations in and around New York state reveals much the same seismic pattern as is discernible from a wider base of more sparsely spaced stations. In particular certain seismic gaps occur within belts of high seismicity. This implies that seismicity is dependent not only on regional stress but also on the availability of suitably oriented faults.

Schafer, K., 1979. Recent thrusting in the Applachians. Nature, vol. 280, pp. 223-226.

Ten-year old boreholes in central Penn. offset by 15 to 140 mm by NE to SW aligned thrusting. Not glaciated.

Scheidegger, A.E., 1975. Geotectonic interpretation of measurements of joint orientations in the Muskoka region of the Canadian Shield. Annali di Geofisica, vol. 28, no. 4.

Used joint orientation data to determine stress trajectories for Muskoka area. Observed that the principal regional stresses correspond to the pattern of fresh fractures (but not to the old Precambrian fractures) which fits with the principal geographic features of the region, including the strike of the St. Lawrence Valley. In addition the author shows a photograph of a well developed joint (indicated by offset) in Quaternary sands and gravels.

Sissons, J.B. and Cornish, R., 1982. Differential glacio-isostatic uplift of crustal blocks at Glen Roy, Scotland. Quaternary Research, vol. 18, pp. 268-288.

Some glacial lake shorelines horizontal, some tilted 4.6 m/km, some distorted up to 3 m above average level. All within limits of glacial advance, possible association with glacial lake filling and emptying. Probably accomplished prior to 6.8 ka BP.

Stansfield, J., 1915. The Pleistocene and Recent deposits of the island of Montreal. Geological Survey of Canada Memoir 73, 80 pp.

Sands and gravels displaced by small faults with throw of up to about 30 cm.

Stein, S., Sleep, N., Geller, R.J., Wang, S.C. and Kroeger, G.C., 1979. Earthquakes along the passive margin of eastern Canada. Geophysical Research Letters, vol. 6, pp. 537-540.

The focal mechanisms of 7 earthquakes along the eastern margin of Canada are deduced from seismic records of the events. The focal mechanisms are claimed to fall into two classes according to whether the epicentre lies landward or seaward of the 1000 m bathymetric contour. Those occurring landward involve normal faulting while those occurring seaward involve reverse faulting. This pattern is analysed in terms of a simple flexural model of deglaciation and shown to be consistent with the behaviour of a collapsing peripheral bulge beneath the seaward quakes and a rebounding region beneath the landward quakes. The difficulty with the paper is the simplicity of the flexural model and the poor statistics of the focal mechanism analyses. Quinlan has questioned some of these results.

Stephansson, O. and Carlsson, H., 1980. Seismo-tectonics in Fennoscandia. in 'Earth rheology, isostasy and eustasy.' edited by N-A. Morner, Wiley, pp. 327-337.

Seismo-tectonic map shows earthquakes located on tectonic welts, including the Tertiary Western Norwegian zone, the Permian graben and the older Lapland zone. Urges need to obtain more dates and information to confirm postglacial age of faults - should date new minerals along slickensides.

Thompson, W.B., 1979. Postglacial faulting along the Norumbega Fault zone. Maine geologist, vol. 5, no. 3, 6 pp.

Six exposures show postglacial displacements oriented 050°, throw of 1.5 to 30 mm, up to 10 cm long. Scarp direction variable.

Vanicek, P., 1976. See section B1.1.

Walcott, R.I., 1970. Isostatic response to loading of the crust in Canada. Canadian Journal of Earth Sciences, vol. 7, pp. 716-726.

The free-air gravity anomaly over Canada is used to show that the central region of the former Laurentide ice sheet is still incompletely recovered and that there may be 250 - 450 m of rebound yet to occur near Hudson Bay. This conclusion is highly biased by assumptions as to the equilibrium value of the gravity anomaly in the area. Stress calculations are presented that show the region of maximum stress beneath an ice sheet will be 200 - 300 km inside the edge of the sheet and that, for an ice sheet 2 km thick, this stress would be about 40 MPa. Laboratory measurements of the strength of peridotite suggest that the elastic limit of such rocks is less that 200 MPa. During growth of ice sheets, therefore, stress could increase beyond the elastic limit resulting in either plastic flow or fracture of the rock.

Wallach, J.L. and Prucha, J.J., 1979. Origin of steeply inclined fractures in central and western New York state: Summary. Geological Society of America Bulletin, 90, pp. 417-421.

Fractures may be incipient normal faults due to dissolution of evaporites since they are most conspicuous and abundant in the area containing slump folds related to dissolution at depth.

Weichert, D.H., 1985. New Brunswick strong ground motion records. Physics of the Earth and Planetary Interiors, vol. 38, pp. 83-91.

The 5.7 magnitude earthquake of Jan 9, 1982 caused only slight architectural damage but was felt at ground level up to distances of 400 km. Aftershocks defined 2 N-S striking planes dipping east and west respectively along which a wedge of upper granitic crust was thrust up by the inferred regional east-west compression. The main shock appears to have ruptured the eastern plane from a depth of 7 km upward while the principal aftershock of Jan 11 appears to have ruptured the western plane. Minor surficial evidence of rupture has been found in the epicentral areas and is described by Basham and Adams (1984).

White, O., Karrow, P.F. and Macdonald, J.R., 1973. Residual stress relief phenomena in southern Ontario. Proceedings of the 9th Canadian rock mechanics symposium, Montreal, pp. 323-348.

Two folds of postglacial age. One 500 m long, 070° orientation, 1 m high and at least 3.2 m deep. Other is 2100 m long, 090° orientation, <1 m high. Faults not certainly postglacial. Thrust, oriented 000°, 0.6 m throw.

Williams, H.R., Corkery, D. and Lorek, E.G., 1985. A study of joints and stress-release buckles in Paleozoic rocks of the Niagara peninsula, southern Ontario. Canadian Journal of Earth

Sciences, vol. 22, pp. 296-300.

Stress-relief buckles and dominant joints oriented 135, compressive force from 050°.

Wold, R.J., Isachsen, Y.W., Geraghty, E.P. and Hutchinson, D.R., 1977. Seismic-reflection profiles of Lake George, Adirondack Mountains, New York, as a guide to the neotectonic history of the region. Geological Society of America, Abstracts with Programs, vol. 9, no. 7, p. 1233.

Several growth faults with vertical displacements up to 24 m in sediments up to 120 m thick. May be related to NNE graben of lake.

Woodworth, J.B., 1905. Ancient water levels of the Champlain and Hudson Valleys. New York State Museum Bulletin 84, 265 pp.

Postglacial faults east of Albany and other locations; measurable, but no values given.

Woodworth, J.W., 1907. Postglacial faults of eastern New York. New York State Museum Bulletin 107, 28 pp.

Faults strike 009°, up to the east, 2.5 to 12 cm. Two other similar locations described. Pumpkin Hollow, 50 cm displacement.

York, J.E. and Oliver, J.E., 1976. Cretaceous and Cenozoic faulting in Eastern North America. Geological Society of America Bulletin 87, pp. 1105-1114.

Postglacial faults in NS and NY show previous earlier displacements, indicating postglacial movements are a continuation of older deformation, or a reactivation of older faults.

3. Fracture Frequency Due to Glacial Loading, Erosion and Tectonic Stress.

Carlsson, L., Winberg, A. and Rosander, B., 1983. Investigations of hydraulic properties in crystalline rock. Proceedings 7th International Symposium on the Scientific Basis for Nuclear Waste Management, Nov. 14-17, 1983, Boston, Mass.

Authors summarize the permeability and fracture frequency data as a function of depth at several sites in Sweden. They suggest that there is a general decrease of conducting fractures with depth. However there is no real indication that fracture frequency increases or decreases with depth.

Haxby, W. F. and Turcotte, D.L., 1976. Stresses induced by the addition or removal of overburden and associated thermal

effects. Geology, (March), pp. 181-184.

A theoretical study that examines the potential role of erosion in the development of the state of stress in the crust. The stress state induced by erosion is broken down into three separate components: stresses due to the reduction of overburden pressure, stresses due to uplift on a sphere, and thermal stresses. During erosion the stress due to removal of overburden pressure is compressional, whereas the stresses due to uplift on a sphere and the thermal stresses are tensional. The authors found that the latter stresses dominate and hence erosion leads to predominantly tensional stresses. The authors suggest that an erosion rate of 1 km/ma represents the most rapid rate of erosion expected in active tectonic regions. Given the low tensile strength of rocks one would expect fractures to be created in unfractured rocks and opened in fractured rock masses.

Stephansson, O., 1977. Deformationer i sprickigtberg (Deformations in fissured rock). KBS Technical Report No. 29, SKB, Stockholm, Sweden.

Computer analysis of the response of a fractured rock mass to boundary stresses. The strength of the rock mass is assumed to be governed by the Coulomb-Navier criterion, resulting in one set of tensile fractures and two sets of shear fractures. The numerical modelling results suggested that areas (4 km x 4 km) with joint spacings of 1 per square metre, bounded by large shear zones, will accomodate reasonable changes in tectonic stresses without developing large cross-cutting fractures.

4. Differential Movement of Adjacent Blocks Due to Glacial Loading, Erosion and Tectonic Stress.

Adams, J., 1981. Postglacial faulting: a literature survey of occurrences in eastern Canada and comparable glaciated areas. Atomic Energy of Canada Technical Report 142, 63 pp.

See discussion in section B 1.1.

Basham, P.W., Forsyth, D.A., and Wetmiller, R.J., 1977. The seismicity of northern Canada. Canadian Journal of Earth Sciences, vol. 14, pp. 1646-1667.

A catalogue of seismicity in northern Canada with speculation as to the relation between seismicity and postglacial rebound.

Brown, L.D., 1978. Recent vertical movement along the east coast of the United States. Tectonophysics, vol. 44, pp. 205-231.

See discussion in section B 1.3.

Clark, J.A., 1976. Greenland's rapid postglacial emergence: A result of ice-water gravitational attraction. Geology, vol. 4, pp. 310-312.

See discussion under section B 1.1.

Farrell, W.E. and J.A. Clark, 1976. On Postglacial sea level. Geophysical Journal of the Royal Astronomical Society, vol. 46, pp.647-668.

See discussion in section B 1.1.

Sanford, B.V., Thompson, F.J. and McFall, G.H., 1985. Plate tectonics - a possible controlling mechanism in the development of hydrocarbon traps in southwestern Ontario. Bulletin of Canadian Petroleum Geology, v. 33, pp. 52-71.

See discussion in section B 2.3.

Walcott, R.I., 1972. Past sea levels, eustasy and deformation of the Earth. Quaternary Research, vol. 2, pp. 1-14.

See discussion in section B 1.1.

Walcott, R.I., 1972. Late Quaternary vertical movements in Eastern North Americ: quantitative evidence of glacio-isostatic rebound. Reviews of Geophysics and Space Physics, vol. 10, pp. 849-884.

See discussion in section B 1.1.

5. Changes in Groundwater Systems as a Result of Upward Vertical Movement.

5.1 Changes in Groundwater Systems Due to Faulting and Fracturing.

Burdon, D.J., 1977. Flow of fossil groundwater. Quarterly Journal Engineering Geology, vol. 10, pp. 97-124.

This paper analyses conceptual mechanisms for maintaining groundwater flow in arid regions which have no significant modern recharge. Of seven possibilities considered, the three most relevant for our purpose are: 1) relict heads, cf Toth (1978); 2) regional tectonic tilting of a basin; and 3) localized downdrop of discharge zones, leading to renewed groundwater flow. Of these, (3) is considered to be one of the most important causes, wherein faulting is the agent responsible for rejuvenating the regional hydraulic gradient. Similar results would obtain if faulting juxtaposed previously offset permeable horizons.

Coltorti, M. and Nanni, T., 1983. Hydrogeology and neotectonics of the lower Esino Basin, Central Italy. International Conference Groundwater and Man, Sydney, vol. 3, pp. 11-22.

Geochemistry of Ca-HCO_3 groundwaters in alluvial fans shows that near surface local groundwaters of low salinity and recent origin, are mixing with high salinity groundwater originating from Lower Pleistocene sandstones, and which is interpreted to be deep, regional 'fossil salt water'. Upflow of this deeper, older saline water is postulated to be controlled by Quaternary faults below, and in, the alluvium. Faulting was related to Middle Pleistocene uplift of the area, and was probably reactivated following marine transgression and emergence.

Henkel, H., Halt, K., Erikkson, L. and Johansson, L., 1983. Neotectonics of northern Sweden - geophysical investigations. KBS Technical Report 83- 57, 64 pp.

A study of Quaternary faulting in Sweden suggested that movement was associated with deglaciation, primarily along pre-existing zones of weakness in bedrock. Major conclusions include: different fault zones moved independently at different times; and these faults are associated with hydraulically-conductive, water-bearing zones. Mention is made of drilling through an artesian-pressured water-bearing fault zone. The long-lived history of these zones is evident in their abundant Holocene(?) fracturing, brecciation and several kinds of fracture mineralization.

Larsson, I., 1972. Groundwater in granite rocks and tectonic models. Nordic Hydrology, vol. 3, pp. 111-129.

A study of fractures and faults in a Swedish granitic pluton. Lineaments are characterized as tension and shear faults, with corresponding high or low hydraulic conductivities. The study underscores the tectonic control of localized groundwater flushing in crystalline rocks.

5.2. Changes in Groundwater Systems due to Regional Strain and Tectonic Movement.

Berry, F.A.F., 1973. High fluid potentials in California Coast Ranges and their tectonic significance. AAPG Bull., vol. 57, pp. 1219-1249.

Abnormally high fluid pressures in the Great Valley in an extensive zone (500 x 80 miles), is ascribed to plate tectonic movements involving lateral compression directed on both sides of the San Andreas Fault. The greatest effect is seen in shales being squeezed between predominantly granitic blocks of the Sierra-Klamath and Salinas areas. Temperature-driven dehydration reactions are dismissed as a cause of over-pressure, as are relict hydraulic heads from Cretaceous-Eocene time. The abnormal fluid pressures are estimated to represent late Cenozoic

compression.

Bradley, J.S., 1975. Abnormal formation pressures. AAPG Bull., vol. 59, pp. 957-973.

The primary causes of abnormal fluid pressures in reservoirs are considered to be: 1) epeirogenic movement with deposition or erosion; and 2) temperature changes of fluids. For the former case, changing elevations of recharge versus discharge zones create an 'inherited' pressure distribution, different from the normal pressure expected for present topographic and water table elevations. In the latter case, temperature changes may accompany epeirogenic movement primarily due to sediment deposition/erosion; volcanic/intrusive events; salt dome formation; and glaciation. The relatively high coefficient of thermal expansion of water and brine compared to sediment grains (40 to 80 times as great per ^{o}C) is considered significant. Thus, for example, sedimentation and burial would increase T along the geothermal gradient and lead to increased fluid pressure; erosion could have an opposite effect.

Goguel, J., 1978. Hydrogeologie et tectonique. in Implications of hydrogeology for the other Earth Sciences, Proc. meeting; Memoires du Centre d'Etudes et de Recherches Geologiques et Hydrogeologiques, Memoire hors Series, Montpellier, France, pp. 591-594.

A brief review article of limited depth, which recognizes the existence of abnormal hydrostatic pressure and discusses possible causes of overpressure due to tectonic processes. Long-lived overpressure is ascribed to such processes as compaction and gas saturation, whereas transient overpressure due to tectonic effects may be due to frictional heating and rapid loading accompanying fault movement.

Latynina, L.A., 1982. Hydrogelogic effects in deformation of the earth's surface. Akad. NAUK SSSR Izvestiya, Phys. Solid Earth, vol. 17, pp. 812-816.

Changes in the hydrogeological regime, as measured by yearly variations in precipitation input, correlate with rock strain measurements. This interpretation emphasizes that not only changes in the rock matrix can affect the hydrogeological system, but vice versa; rock and water thus are interacting on time scales of years, and changes in fluid and solid phases cannot be considered independently in evaluating the response of the hydrogeologic system.

5.3 Changes in Groundwater Systems due to Erosional Unloading.

Dickey, P.A. and Cox, W.C., 1977. Oil and gas in reservoirs with subnormal pressures. AAPG Bull., vol. 61, pp. 2134-2142.

This review of occurrences of sub-normal pressure in reservoirs considers the primary cause to be erosional unloading of confined or semi-confined porous strata and low-permeability units.

Menely, W.A., Freeze, R.A., Lin, C.L. and Pearson Jr. F.J., 1982. Hydrogeology Program Review. Atomic Energy of Canada Ltd. Technical Record 198, 16 pp.

An important position paper emphasizing the need to better understand the effect of deglaciation and erosion on regional flow systems. "Glacial erosion and isostatic rebound have disrupted the hydraulic equilibrium of the regional groundwater flow systems. It also recognizes the need to understand how deep brine in shield areas originated, and the implications of its presence with respect to residence times and ratios of its mixing upwards...". Recommendations for research focus on salinity/depth relationships, origin(s) of brines, and whether the present flow system is in equilibrium with present topography.

Neuzil, C.E., 1985. Comment on "Possible effects of erosional changes of the topographic relief on pore pressures at depth" by Toth and Millar. Water Resources Research, vol. 21, pp. 895-898.

A critique of Toth and Millar's (1983) (see comments in section B6.3) assertion that relict pre-erosion hydraulic heads could persist over geological time intervals. This paper argues that Neuzil and Pollock's (1983) hypothesis of abnormally low pore pressures created in rocks of very low hydraulic diffusivity during erosional unloading is more reasonable, not only in light of available data but because it takes into account elastic deformation of the rock.

Neuzil, C.E. and Pollock, D.W., 1983. Erosional unloading and fluid pressures in hydraulically "tight" rocks. Geology, vol. 91, pp. 179-193.

Theoretical arguments and some field observations suggest that pore pressure decrease in response to erosional unloading of rocks of low hydraulic diffusivity (principally shales, although some very tight crystalline rocks could also qualify) can be significant, even to the point of producing pore tension. The most obvious consequence of such an erosionally-induced pressure redistribution would be fluid inflow to the affected rock; however, other possibilities include two-phase formation/degassing of pore fluids, and decreased permeability (due to desaturation aand vapour phase formation).

Russell, W. L., 1972. Pressure-depth relations in the Appalachian region. AAPG Bull., vol. 56, pp. 528-536.

Lenticular reservoirs of pre-Pennsylvanian age, in the

Appalachian region, show sub-normal pore pressures in many cases. These abnormally low fluid pressures are attributed to erosional unloading of shales which subsequently transmit this pressure reduction to adjacent porous reservoirs. Pressure/depth ratios as low as 30 percent of normal values have been observed in Devonian shales in West Virginia, and as low as 50 percent of normal, in Lower Cretaceous sandstones.

Toth, J., 1978. Gravity-induced cross-formational flow of formation fluids, Red Earth region, Alberta: analysis, patterns and evolution. Water Resources Research, vol. 14, pp. 805-843.

Consideration of a wide range of data, including pressure-depth relations, hypsographic curves of topographic and water table elevations, and pressure increment patterns, indicate that the Cenozoic and Mesozoic/Paleozoic strata of this region of north-central Alberta have a near-equilibrium hydraulic head distribution for present-day topography. The lowermost Devonian aquifer also shows a topographically- controlled head pattern, but with values in excess of normal present-day hydrostatic heads. It is argued that this excess pore pressure represents a relict head distribution reflecting Pliocene topography, which has slowly been readjusting to present topography following erosional exposure of a major unconformity that in effect represents an hydraulic drain for the upper hydrogeologic units but not the basal Devonian aquifer.

6. Readjustment Time of Groundwater Systems Due to Changes in the Geological Environment.

6.1 Groundwater Readjustment Time Pertaining to Faulting and Fracturing.

Jacks, G. 1972. Chemistry of groundwater in igneous rocks at Angered, Gothenburg. Nordic Hydrology, vol. 3, p. 140.

Jacks, G., 1973. Chemistry of some groundwaters in igneous rocks. Nordic Hydrology, vol. 4, p. 207.

Qualitative age estimates of groundwater in fractured crystalline rocks of Scandinavia, based on salt content of mixed seawater-groundwater fluids relict from an isostatically-depressed regime, suggest that very little groundwater flushing has occurred below 100 m on a time scale of 10^4 years; shallow groundwater, in contrast, has relatively low salinity, indicating active groundwater movement; fluids in sheared, high-permeability zones are clearly distinguished by lower chloride contents, demonstrating higher groundwater through-put and rates of readjustment to changing geochemical and hydrological conditions.

6.2. Groundwater Readjustment Time Pertaining to Regional Strain and Tectonic Movement, Including Glaciation and Deglaciation.

Allard, B., Larson, S.A., Tullborg, A.-L. and Wikberg, P., 1983. Chemistry of deep groundwaters from granitic bedrock. KBS Technical Report 83-59, 47 pp. plus appendices.

A discussion of the chemistry of deep borehole waters in Sweden. Of greatest relevance are the documented instances of high Cl saline waters (up to 650 ppm TDS) in close proximity to, and even surrounded by, non-saline water, which "indicate a very slow water exchange and possibly high age of the saline waters." Carbon-14 ages up to 15,000 years are reported (with no indication of the method of calculation), although these maximum ages were also found in non-saline as well as saline groundwaters. Possible origins of these and other saline groundwaters are discussed in an Appendix, with the conclusion that the most likely sources are relict Baltic seawater, intruded during glacial isostatically depressed conditions 3,500-8,000 years ago, or residual igneous/metamorphic fluids and/or fluid inclusions (probable age > 10,000 years). The two possibilities could be distinguished on the basis of Ca/Mg, Mg/Cl and Br/Cl ratios, hence placing rough age constraints on these waters.

Jacks, G., 1978. Ground water chemistry at depth in granites and gneisses. KBS Technical Report 88.

Simple inundation of coastal areas is considered inadequate to explain salt water encroachment into crystalline rocks of Sweden (no hydraulic gradient, insufficient density contrast). It is proposed that marine sediments deposited on inundated crystalline areas are the source of marine salts, and that the present location of salty deep groundwaters depends on the transient history of salt flushing out of clays into the crystalline rocks, and subsequently, flushing of the latter by fresh meteoric waters.

Lahermo, P.W. and Lampen, P.H., 1985. Brackish and saline groundwaters in Finland. Presented at Geological Association of Canada Symposium on brines, May 1985 (to be published in Geological Association of Canada Special Paper on Proc. of Symp.).

Coastal groundwaters at 100-200 m depth are characterized by brackish to saline fluids representing transgression of Baltic Sea 5,000-7,000 years BP while the region was isostatically-depressed; major ion ratios are similar to seawater; inland, saline groundwaters are much less common, but where they occur, represent either a highly evolved (ie. old) seawater, or groundwater modified extensively through low-T water-rock reactions; a 1 km research borehole 100 km from the coast shows no abnormal salinities, possibly suggesting that

seawater transgression is localized or that its effects are retained to varying degrees depending on the extent of groundwater flushing.

6.3 Groundwater Readjustment Time Pertaining to Erosional Unloading.

Couture, R.A., Seitz, M.G. and Steindler, M.J., 1983. Sampling of brine in cores of Precambrian granite from northern Illinois. Journal of Geophysical Research, vol. 88, pp.7331-7335.

Couture, R.A., Seitz, M.G. and Steindler, M.J., 1985. Groundwater chemistry at depth in granite basement, northern Illinois. Submitted to Geology, June, 1985.

Salinity gradient in pore fluids in Precambrian granite basement, perhaps derived from formation fluids of the Illinois Basin, implies that little or no fresh water replacement has occurred below 500 m in the granite (ie. to 1160 m present depth below surface). Diffusion calculations suggest that a diffusion mechanism could explain the observed salinity gradient, and that saline groundwater remaining in the granite basement has not been flushed for > 10^7 years.

Toth, J. and Millar, R., 1983. Possible effects of erosional changes of the topographic relief on pore pressures at depth. Water Resources Research, vol. 19, pp. 1585-1597.

In attempting to account for the pore pressure distribution in the basal Devonian aquifer of the Red Earth Region, Alberta, which Toth (1983) ascribed to relict Pliocene heads, the authors model the response of an idealized cross-section, representing the hydrogeologic units of the field area, to an instantaneous erosional removal of material from the top of the section. The time available to dissipate the relict over-pressure in the basal unit (3×10^5 - 4×10^7 yr), is consistent with calculated response times using realistic values of hydrogeologic parameters, and supports the contention that relict Pliocene heads are present in the basal Devonian unit.

Toth, J. and Millar, R.F., 1985. Reply; Water Resources Research, vol. 21, pp. 899-903.

In response to a comment by Neuzil (1985) on the validity of their assumptions in modelling the dissipation of excess pore pressures following erosional unloading, the authors argue that Neuzil's assumptions are even less tenable and that on a regional scale, given the degree of hydrogeologic complexity seen in their field area, the effect of rock elastic deformation cannot be modelled properly, and even if it could, it would represent a second-order effect.

6.4 Assessment and Dating of Groundwater Associated with Unspecified Processes.

Frape, S.K. and Fritz, P., 1981. The chemistry and isotopic composition of saline groundwaters from the Sudbury Basin, Ontario. Canadian Journal of Earth Sciences, vol. 19, 645-661.

Frape, S.K. and Fritz, P., 1981. A preliminary report on the occurrence and geochemistry of saline groundwaters on the Canadian Shield. Atomic Energy of Canada Ltd. Technical Record 136, 68 pp.

The occurrence of saline waters deep in the Canadian Shield is widespread. Salinity increases uniformly with depth, with systematic variations in major ion ratios, such as increasing Ca/Na, decreasing Ca/Mg and Ca/K and decreasing HCO_3 and SO_4 with depth. Stable isotope compositions vary systematically also, from near the meteoric water line in fresh groundwaters to very unusual deuterium-enriched / ^{18}O-depleted waters at depth.

Fritz, P. and Reardon, E.J., 1979. Isotopic and chemical characteristics of mine water in the Sudbury area. Atomic Energy of Canada Ltd. Technical Record 35, 37 pp.

Discovery of highly saline brines in deep groundwaters at Sudbury raised the question of their origin, and the rates of deep groundwater circulation. The authors originally proposed either Paleozoic formation waters, altered by low-temperature rock-water interaction, or "moderately old" waters similarly affected. They suggest that the weight of the evidence rules out fluid ages less than "many thousands of years." Carbon-14 analyses of brines sampled in mine workings indicate that modern water is actively flushing the areas disturbed by mining. Aside from such disturbances, they suggest that "active flushing of the lithologic sequences of their pre-Pleistocene formation waters had begun only in the past several tens of thousands of years."

Fritz, P., Al-Mooji, Y., Frape, S.K. and Salati, E., 1983. Saline groundwaters in crystalline rocks, isotopic and geochemical considerations on their origin. International Conference Groundwater and Man, Sydney, vol. 2, 89-98.

A general review of the occurrence of deep saline waters in shield areas, reiterating the hypotheses of their inferred age and common history.

Johnston, L.M., 1982. A review of the geochemistry of groundwater in crystalline rocks. Atomic Energy of Canada Ltd. Technical Record 154, 99 pp.

A summary of literature pertaining to groundwater chemistry in crystalline rocks, including saline groundwaters of Sweden and deep brines of shield areas. Specific discussion is focused on

changes in groundwater chemistry due to rock/water chemical equilibria, with the conclusion that quantitative understanding of groundwater chemical changes in terms of fundamental parameters such as rock type and time is still a remote goal.

Kerrich, R., 1984. Chronology and ambient temperature/pressure conditions of fluid flow through the Eye-Dashwa Lakes pluton based on the $^{18}O/^{16}O$ ratio and fluid inclusions. Atomic Energy of Canada Ltd. Technical Record 267, 31 pp.

Analyses of fluid inclusion filling temperatures in fracture-filling minerals, together with oxygen-18 isotopic analyses in coexisting minerals, indicate that the fluids involved in the fracture mineralization episodes during cooling of the pluton were definitely pre-Pleistocene. However, late clay-coated (low-T) fractures "may have formed in equilibrium with recent surface waters", although verification awaits isotopic analysis of this late mineralization.

Laurent, S., 1982. Analysis of groundwater from deep boreholes in Krakemala, Sterno and Finnsjon. KBS Technical Report 82-23.

A noteworthy discussion of geochemical data from research boreholes in granitic rock, as it pertains to the age of saline groundwaters. Important conclusions and points: 1) a comparison of carbon-14 ages and fresh water - saline water mixing ratios calculated from $^{234}U/^{238}U$ data indicate close agreement, and support the concept of mixing of old (> 10,000 years) and modern waters; 2) stable isotope data show little or no shift due to rock-water exchange, even for waters with ^{14}C ages > 10,000 years; 3) dissolved gas analyses show 8.5 - 9.4 percent helium, an extraordinarily high value, and suggest either very high U/Th ratios in the host rocks, or great age of the water; 4) carbon-14 contents indicate conventional ages to 12,000 years.

Tullborg, E.-L. and Larsson, S.A., 1982. Fissure fillings from Finnsjon and Studsvik, Sweden. KBS Technical Report 82-20, 76 pp.

Three generations of calcite, the most abundant fracture-filling mineral in these granitic rocks, were identified: 1) early, closed fracture hydrothermal calcite; 2) late calcite deposited in oxygen isotopic equilibrium with present-day water; and 3) calcite deposited from a fluid enriched in ^{18}O relative to present-day meteoric water. High salinities of fluid inclusions suggest Baltic seawater. Significantly, the late fresh water calcites indicate that some fissures have been active quite recently, "during the last deglaciation or even later." Uranium-series dating of calcites indicates calcite generation younger than $29 \pm 13 \times 10^3$ years. Thus, evidence points to Quaternary deposition of calcite, possibly involving Baltic seawater during or after the last glaciation, with fresh water deposition continuing possibly to the present.

C. SUMMARY OF INFORMATION CONTAINED IN ANNOTATED BIBLIOGRAPHY

1. Strain Rate

1.1 Strain Rate Due to Glacial Unloading

A great deal of effort over the last 100 years or so has gone into investigation of the time-dependent deformation of the Earth's surface following deglaciation. Deformation patterns, evident from mapping a variety of deformation phenomena, hold clues as to the mechanical behaviour of the Earth's interior and, for this reason, the mapping has been accompanied in recent years by significant theoretical work. The result is that glacio-isostatic rebound is one of the more thoroughly studied and better explained of global phenomena.

A complete bibliography of observations relating to glacio-isostasy would be an enormous undertaking. Fortunately, it is not necessary within the context of this report. This is because the range of observed strain rates is rather limited and because the well-developed theoretical framework for glacio-isostasy makes radical departures from this range unlikely. The best approach to discussing this topic is to describe the theory on which glacio-isostatic adjustment is based and then to describe the range of strain rates within the context of the model framework.

1.1.1 Theory of Large Scale Postglacial Adjustment

Significant mass is transferred between the continents and the ocean basins during buildup and decay of large ice sheets associated with continental glaciation. For example, the Laurentide Ice Sheet that covered most of the Canadian landmass ca. 20,000 BP had an estimated total mass of $2.5\text{-}3.0 \times 10^{10}$ kg (Flint, 1971). Such loads can deform the Earth's surface with this deformation being recovered following melting of the ice sheets. Neither the glacial deformation nor the postglacial recovery is instantaneous. This is because, in order for the surface of the Earth to move up or down, there must be a sympathetic transfer of material within the Earth's mantle away from subsiding regions and toward uplifting regions. The viscosity of the Earth's mantle dictates the rate at which deformation and rebound can occur. Postglacial rebound associated with removal of the Laurentide Ice Sheet continues at a measurable rate in parts of Canada. Cathles (1975, p. 353) showed present rates of rebound on the order of 1 cm/yr in the most recently deglaciated areas of Canada (ca. 7,000 BP).

The record of postglacial deformation is preserved in a series of strandline indicators formed at sea level and now found elevated above or submerged below present sea level. These indicators are typically shells, driftwood, peat or other organic materials that can be both related to past strandlines

and dated using ^{14}C or other radiometric techniques. Analysis of strandline indicators (called relative sea level or RSL data) constrain the spatial and temporal characteristics of the Earth's deformation in response to deglaciation. There are few direct indicators still preserved in the geological record to document the Earth's response during the buildup phase of a glacial cycle. For this reason we will concentrate on analysis of postglacial adjustment and appeal to symmetry when considering glacial buildup.

It is important to note that the shapes of both the Earth's surface and the sea surface change in response to the waxing and waning of ice sheets. RSL data record only the net change in separation of the two surfaces and are not, therefore, direct measurements of crustal deformation per se. Conceptually the relationship between observed RLS changes at a location (x), isostatic crustal deformation I(x) and eustatic changes in sea surface position E(x) is given by the equation (e.g. Quinlan and Beaumont, 1981).

$$RSL(x) = E(x) - I(x)$$

The negative sign implies that a rise in eustatic sea level has the same effect on RSL as does a fall in land level. This equation provides the basis for the classical approach to determining crustal deformation from RSL observations. As we will see shortly this approach is incorrect. Nevertheless, it is worthwhile discussing it briefly because it is so widely employed in the literature.

Clearly a measurement of RSL at a site cannot be separated uniquely into values of "I(x)" and "E(x)" unless one or the other is known independently. The usual method of attempting such a separation is to measure "RSL" at a site remote from glaciation (e.g. Shepard and Curray, 1967). The assumption is that, since this site was not glaciated, crustal deformation "I" is negligible and so a measurement of "RSL" gives "E" directly. A graph of "E" as a function of time is then taken to measure the fluctuation of water volume in the oceans as ice sheets ablated and meltwater returned to the oceans. Such 'eustatic curves' are often applied at sites near former ice sheets on the assumption that meltwater is uniformly distributed throughout all the ocean basins following deglaciation.

There are three potentially fatal flaws in such an approach. First, and most obviously, we must be assured that the measurements of RSL were not made at tectonically disturbed sites. Second, the ocean basins are loaded by the addition of meltwater and must subside isostatically beneath the load. This means that no site, however far from an ice sheet, is truly free of isostatic deformation "I". Third, the surface of the ocean corresponds to an equipotential surface of the Earth's gravity field (the geoid) and so the shape of the sea surface reflects the distribution of mass on and within the Earth's surface.

Ablation of large ice sheets and redistribution of the meltwater alters the surface mass distribution and also requires mass redistribution within the Earth's mantle to accommodate postglacial rebound. Since ice sheet distribution is non-uniform over the Earth's surface, it follows that rebound-induced changes to the geoid cannot be spatially uniform. This means that different amounts of meltwater will be distributed to different areas of the ocean basins. Even if it were possible to isolate "E" at one site, there is no reason to believe that this value is applicable elsewhere.

This qualitative analysis has important implications for much of the literature on postglacial adjustment. When reading any paper one must be critical of attempts to define eustatic sea level curves and attempts to interpret RSL data as uplift data.

A major breakthrough in understanding postglacial adjustment came with the numerical modelling work of Farrell and Clark (1976) building upon that of Peltier (1974) and Peltier and Andrews (1976). These studies quantified the ideas discussed qualitatively above. Global models of postglacial RSL change were constructed in which RSL could be calculated as a function of position and time following the melting of any arbitrary ice configuration. The model results are sensitive to both the assumed global ice configuration and the assumed rheological parameters of the Earth. By adjusting model assumptions, it is possible to find sets of ice and Earth representations that jointly satisfy the observed values of RSL for sites both near to and remote from centres of glaciation. Quinlan (1981,1985), and Quinlan and Beaumont (1981, 1982) have adapted these global models to look at the RSL record within eastern and arctic Canada in $1^{o}x1^{o}$ spatial detail. The advantage of such models is that they calculate RSL histories for direct comparison with observations; no separation of observations into isostatic and eustatic components is necessary. A model that can account for RSL variations at observation sites can also be used to estimate RSL variations for sites where no observations exist. In addition, a minor variation of the model can be used to calculate only the isostatic component of RSL. This approach provides a means of estimating crustal rebound at any arbitrary site from a model known to be consistent with observed values of RSL change. Such a calculation is clearly of some significance in estimating the magnitude of crustal stress, strain and strain rate associated with deglaciation. As a first approximation, Quinlan and Beaumont (1981) show in their Fig. 10 that the maximum rate of crustal rebound in the post glacial phase is not greatly different from the maximum rate of RSL adjustment for sites in and near formerly glaciated areas. This means that strain rates for such areas can be reasonably approximated by using rates of RSL change. The same cannot be said of the actual magnitude of uplift compared with the magnitude of RSL change.

Another important suggestion of such models is that formerly glaciated and glacier-marginal areas are naturally divided into

four zones on the basis of the character of the RSL curves. RSL curves within any one zone have a common shape although the magnitude of such curves vary smoothly from site to site within the zone. RSL curves vary in shape among the four zones. The physical rationale for this zonation is as depicted in Figure 1. At the glacial maximum the region beneath the ice sheet is isostatically depressed. The mantle material pushed out from beneath the downwarped area forms an upwarped peripheral bulge beyond the ice sheet periphery. As the ice sheet melts, this bulge follows the retreating ice edge in toward the centre. The rate of bulge migration is controlled by the high viscosity of the Earth's mantle which must flow in order to allow bulge migration. Figure 1 shows the position of the peripheral bulge at two times: at the glacial maximum and at the present. Locations A-D represent four sites situated at different distances from the ice sheet centre. Location A is closest and loacation D is furthest from the centre. As the bulge moves inward (in the direction of the arrow) each site is carried up or down by the bulge much as a cork would be on a passing wave. Site A is still on the inward side of the bulge at present and so has experienced continuous uplift since the glacial maximum. Site D has always been beyond the crest of the bulge and so has experienced continuous subsidence throughout postglacial time. The bulge crest has passed by each of sites B and C first uplifting and then downwarping them. The difference between sites B and C is that site B has experienced relatively more uplift and relatively less subsidence than has site C. Both sites B and C are currently submerging but site B has raised marine features of postglacial age while site C does not. This RSL zonation corresponds closely to what is seen in the field. For example, the region from Hudson Bay to the Gulf of St. Lawrence is presently emerging (zone A). Farther from the former ice centre, the New Brunswick shore of the Bay of Fundy is currently submergent but has significant raised marine features (zone B). Still farther from the ice centre, the Atlantic coast of Nova Scotia is currently submerging but has no raised marine features (zone C). Presumably the offshore area lies within zone D but this is difficult to prove because of the lack of datable horizons related to RSL.

This zonation scheme is extremely useful for present purposes. It means that we can discuss some typical rebound curves observed from each of the four major zones and be reasonably sure that we have covered the range of postglacial behaviour. The rates quoted below are based on observations cited in Peltier and Andrews (1976) and Quinlan and Beaumont (1981).

a. Zone A Strain Rates

RSL at a site near the Ottawa Islands in Hudson Bay fell ca. 70 metres in the first 2,000 years following inception of ice-free conditions ca. 7,000 BP. Using the rate of this fall as a measure of the strain rate gives the rate as 1.7×10^{-16} sec^{-1}. The average strain rate over the next 1,500 years was 1.3 x .

10^{-16} sec^{-1} and over the most recent 3,500 years was 0.3 x 10^{-16} sec^{-1}.

For a site in northwestern Newfoundland the strain rates varied from 0.7 x 10^{-16} sec^{-1} to 0.2 x 10^{-16} sec^{-1}.

b. Zone B Strain Rates

The RSL record for western Prince Edward Island is not as complete as for the two zone A sites, yet it seems to suggest a maximum strain rate of 0.6 x 10^{-16} sec^{-1} decreasing to 0.1 x 10^{-16} sec^{-1}.

c. Zone C Strain Rates

Eastern Prince Edward Island has been subjected to strain rates on the order of 0.3 x 10^{-16} sec^{-1}.

d. Zone D Strain Rates

No reliable data exist for zone D sites because their entire postglacial history was one of rising RSL. For this reason most such sites are presently under water and difficult to observe directly. It seems unlikely that such sites would experience strain rates much different from sites in zone C.

1.2 Strain Rate Due to Erosion

Erosional removal of loads on a regional scale is mechanically identical to removal of glacial loads; both produce uplift by purely isostatic processes. For this reason, we might reasonably expect the strain rates due to erosion to be no greater than those produced by glacio-isostasy. There appears, however, to be little direct discussion of this process in the literature particularly as it pertains to short-term erosion. The reason for this no doubt lies in the relatively minor magnitude of erosional unloading that occurs over short time scales and large spatial scales. In order to have erosion of a significant enough magnitude to be measured accurately, the process must be allowed to act over timescales on the order of millions of years. This in turn means that resulting strain rates must be averaged over comparable timescales. Stephenson and Lambeck (1985), for example, discuss erosionally induced uplift in south-eastern Australia during the Cenozoic. If uplift of 1,500 m did occur, as they suggest, since the Cenozoic began then this implies an average strain rate of 1.2 x 10^{-19} sec^{-1} or three orders of magnitude smaller than glacio-isostatic uplift. There is some debate as to the exact time of the onset of erosion; it may be as recent as late Pliocene-Pleistocene. In this case the strain rate would be 3 x 10^{-18} sec^{-1}, still two orders of magnitude less than glacio-isostatic rates.

An extensive literature does exist which describes the rates of modern-day erosion of denudation in eastern North America, the

consequences of subaerial erosion during the Mesozoic and Cenozoic, and the amount of erosion effected by ice during the Cenozoic.

Modern denudation can be estimated from the sediment yield of major rivers. Milliman and Meade (1983) determined that the total sediment load delivered by all rivers in ca. 15 x 10^9 tonnes/year, with >70% of that from south Asia and the Pacific Rim. The world average sediment yield of 116 tonnes/km^2/year is much higher than rates estimated for the Canadian Shield, <10 tonnes/km^2/year, and for the St. Lawrence area, between 10 and 50 tonnes/km^2/year. Variable rates of denudation can be determined from detailed studies of sediment yields in watersheds in the Appalachians (Reed 1971; Williams and Reed 1972), where sub-basins deliver from 15 to 170 tonnes/km^2/year. Variations are largely controlled by rock type; limestones being associated with low sediment loads. This observation suggests that dissolved loads may be critically important in total denudation. Gregor (1970) tried to assess denudation rates for the world as a whole using geochemical data on the transportation rate of dissolved sodium in rivers. He calculated a present world denudation rate of 24 x 10^9 tonnes/year, which is 60% higher than that calculated by Milliman and Meade (1983), giving an average world sediment yield of 186 tonnes/km^2/year. Gregor maintained that present denudation rates are artifically high due to the activities of man, perhaps two to three times higher than in pre-human eras. A detailed study of rivers flowing into Long Island Sound, using evidence of present sediment load, plus knowledge of the thickness and age of sediments in the Sound (Gordon 1979), do not bear out this point, at least not for the low-sediment yield areas of northeastern North America. Gorden calculated a sediment yield equal to 10 tonnes/km^2/year, which has been unchanged for the last 8,000 years. The low rate of denudation there probably results from a stablised, low-level area of resistant bedrock and compact lodgement till. Most of the present load of the rivers derives from ancient glacial lake sediments which are fluvially eroded during flood events and river bank collapses.

The consequences of subaerial erosion through a time scale of many, perhaps hundreds of millions of years, is the reduction of rugged terrain to land surfaces of low relief, termed "peneplains" in the traditional North American usage, after W.M. Davies, or "pediments" in the more recent European/South African usage, afte L.C. King. It would be pointless to debate the convoluted principles behind these terms; it is perhaps better to avoid both and use the term "upland surface". Not all erosional landsurfaces are uplands, admittedly, although those which are not buried by overlying sediments generally are. Most of the literature on upland surfaces is ancient, although three recent works are of interest. Ambrose (1964) suggested many upland surfaces in the Canadian Shield were very old, much older than their usually-assumed Mesozoic-Cenozoic age. Bird (1972) pursued this theme in the Maritimes, suggesting that many of the

upland surfaces there were probably Paleozoic in age, and only lowland excavation occurred during the Cenozoic. Matthews (1975), using information on the thickness of Cenozoic sediments in the western Atlantic Ocean calculated that between 400 m and 2000 m of rock had been stripped from eastern North America in the last 60 million years. The lower amount applied to northeastern North America, while the higher amount applied to the southeast. These amounts require only very low denudation rates between 0.014 and 0.08 tonnes/km^2/year, assuming an average rock density of 2.8. However, the amount of denudation does suggest that surfaces of great age are unlikely to survive over large areas.

Glaciation has sometimes been charged with responsibility for effecting major erosional reduction of the northern part of the North American continent. A recent version of this viewpoint appeared in 1972 with White's description of deep erosion in North America and Scandinavia. His work relied on the analysis of shapes and sizes of shields, basins and former ice sheets, and has been challenged extensively where his generalizations can be shown to be incorrect at the local level. Gravenor (1975) pointed out that shield rocks are present in the earliest drifts, suggesting the sub-aerial exposure of the shield prior to glaciation. Sugden (1978) examined the surface of glaciated North America, pointing out many areas with little or no sign of glacial erosion. He also pointed out the broad parallels between basal conditions for an ice sheet modelled at the maximum extent, and certain zones of erosion and non-erosion. This lends some credence to the idea that the Laurentide ice sheet persisted at its maximum to create equilibrium landforms for a long period of time at some stage.

Glacial geologists generally regard glaciers as ineffective agents of wholesale erosion, and even regard the stratigraphically-based calculations in Laine (1980) and Bell and Laine (1985) with some doubt. These two works point to the removal of between 55 m and 120 m of rock from the glaciated area of North America in the last 3 million years. Andrews et al (1985) reported late glacial sedimentation rates from Baffin Island fiords as very low, between 0.02 and 0.5 cm/year. Although these cannot readily be expressed in sediment yield terms or denudation terms because of uncertainties of the ice drainage area, they probably represent an order of magnitude less erosion than Bell and Laine (1985). Admittedly, the Baffin rates deal with a narrow time span, and are from the area of the Laurentide which, for reasons of cold ice and resistant bedrocks, may have been one of the sectors where erosion was minimum.

The magnitude of erosion by glacial and subaerial processes during the Cenozoic is clearly not settled. There can be little doubt however that it is much less than the magnitude of mass addition and removal of the ice itself, and was spread over a far longer time span. Thus the strain rates over large areas in

response to Cenozoic erosion are much lower than those resulting from ice loading and unloading, and involve less isostatic compensation and less strain release on rock surfaces. However, a word or two of caution must be offered. Sugden (1978) emphasized the importance of "selective linear erosion" beneath ice sheets, where erosion is concentrated along pre-existing valleys. Locally, rates of erosion, and consequently strain rates, may be very high in such areas where glacial troughs, finger lakes and fiords exist. The presence of "pseudo-bedding" or exfoliation sheets on the walls of such troughs, particularly where they are cut in massive crystalline bedrock, is sufficient evidence of the importance of localized erosion in inducing stress release in rock. G.K. Gilbert, in 1904, was the first to propose the expansion of rock masses when confining pressures are reduced by erosion, and many have subsequently recognized unloading planes parallel to newly-eroded surfaces. W.C. Bradley, writing about the massive sandstones of the Colorado Plateau in 1963 described unloading fractures up to 10 m below the surface. Other text book sources confirm that such fractures will normally be no deeper than 50 m below the surface.

In a classic work on the relationship of sheeting and jointing to topography and glacial history, Chapman and Rioux (1958) presented both field and laboratory data, employing "statistical slope orientation" diagrams and joint orientation to reconstruct preglacial topography in an area of Maine. They noted that since ice advance over the area was oblique to the preglacial topographic plane, glacial erosion was adequate to transform the preglacial monoclinic joint pattern to one of triclinic symmetry. Plumb et al (1984), in a careful study of strain relaxation during overcoring, emphasized that feedback occurs between contemporary tectonic stress, which is generally east-northeast in the area of New York State in which they worked, and the process of jointing during the development of local relief. They introduced the "GCS hypothesis" where near-surface stresses are controlled by stress relaxation associated with weathering and the development of local topography. It is interesting, perhaps significantly so, that these two, and no doubt other works, consider topography and erosion to be dominant over glacial loading and unloading in the development of stress-release joints, at a local scale.

1.3 Strain Rate Due to Tectonic Stresses.

The most dramatic examples of tectonically induced strain are of course earthquakes in which the observable displacement is achieved virtually instantaneously by failure of the outer lithosphere. In such cases measureable strain rate is effectively infinite and so becomes a meaningless concept. There are, however, examples of aseismic vertical movement occurring both in areas of known seismic activity and in areas of virtually no seismic activity.

One of the better studied examples of the former is the Palmdale bulge of southern California. Castle et al. (1976) for example reported crustal uplift of between 15 and 25 cm occurring since 1960 over an area of 12,000 km^2 centred on the junction of the Garlock and San Andreas faults. This area has had no significant seismic activity since 1932. The average strain rate for this uplift is 0.8×10^{-16} sec^{-1} and is presumably due to elastic strain accumulation associated with locking of motion on the fault systems. This average strain rate value may be somewhat misleading since uplift has apparently occurred episodically over the interval. More recently it has been suggested that the uplift is fictitious, being the result of systematic levelling errors (Jackson and Lee, 1979). What seems clear is that, because measurements of small strains are difficult to make accurately, strain rates determined over short time intervals are also difficult to make accurately.

Eastern North America is much less seismically active than is western North America. There are pockets of seismicity such as near La Malbaie in Quebec (Goodacre and Hasegawa, 1980; LeBlanc and Buchbinder, 1977), in central New Brunswick (Basham and Adams, 1984; Weichert, 1985), near Baffin Island (Basham et al., 1977; Stein et al., 1979; Quinlan, 1984), along the east coast U.S. (Sbar and Sykes, 1973, 1977) and in southern Ontario (Sanford et al., 1985). Nowhere has the seismic activity been indisputably associated with a specific tectonic feature as is the case with, say, the San Andreas fault. Detailed levelling studies have been reported by Vanicek and Nagy (1981), Brown (1978) and Brown and Oliver (1976). The pattern described by Vanicek and Nagy (1981) for eastern Canada is consistent with residual glacio-isostatic adjustment whereas the data from the U.S.A. seem to correlate more strongly with older tectonic structures. Brown (1978) showed a consistently increasing rate of uplift from 0.5 cm/yr in Maine to 2.5 cm/yr in Florida but with distinct anomalies in this rate coinciding with structural features such as the Triassic grabens of the northeast and the Cape Fear Arch. Similarly Brown and Oliver (1976) see an west-east trend of decreasing uplift rates from 2.5 cm/yr in Illinois to 1 cm/yr in New Jersey, again with major uplift anomalies correlating with structural features of the Appalachian orogen. The implication of this work is that tectonic stress, perhaps associated with plate tectonic movements, can cause preferential motion on pre-existing structural weaknesses. Vanicek and Nagy (1976) may have found a strong correlation with glacio-isostatic patterns simply because their field area in Canada was formerly glaciated. As such, glacially induced uplift patterns may mask underlying deformational patterns due to other sources.

2. Development and Rejuvenation of Faults and Fractures by Glacially Induced Stress and during Contemporaneous Earthquakes.

Basham et al. (1977) have discussed the unexpectedly high level of seismic activity observed along the east coast of Baffin Island and speculated that this activity may be due to the stress induced by glacio-isostatic uplift of the region. Until the work of Stein et al. (1979), however, there were no published estimates of the magnitude of stress expected from postglacial rebound. Using a very simple model of a 2-D elastic beam flexed by a uniform thickness ice load, Stein et al. estimated maximum stress values of ca. 100 bars and claimed that the variation in stress orientation predicted from this simple model was consistent with variation in the focal mechanisms of seven earthquakes observed along the eastern Canadian margin. In particular, earthquakes occurring seaward of the 1,000 m bathymetric contour involve reverse faulting associated with collapse of a peripheral bulge, whereas earthquakes occurring landward of this contour involve normal faulting associated with uplift of the deglaciated region. If such is true, then it is strong circumstantial evidence for a connection between rebound and earthquakes. It must be kept in mind, however, that failure of the crust occurs in response to the total stress field and rebound-induced stress is only one component of this total field. Without knowing the magnitude and orientation of the background stress, it is not possible to determine whether rebound will trigger earthquakes or stabilize an area against earthquakes that would otherwise occur. Quinlan (1984) has used a detailed model of postglacial uplift to calculate the spatial and temporal variation of crustal stress and discussed an extremal technique for superimposing this calculated stress onto an unknown background stress field. He concluded that postglacial rebound can generate stress levels of ca. 100 bars but found it unlikely that this rebound-induced stress was responsible for the apparent variation in focal mechanisms. The implication is that postglacial rebound can at most act as a trigger for the release of stress built up by other tectonic forces. Something that has yet to be done is to calculate the level of postglacially-induced stress for many areas within Canada and compare these levels with the rate of seismic activity. A significant correlation would strengthen the claim for a relation between rebound and earthquakes. It should be noted that stress is related to the curvature of the rebounding lithospheric plate (e.g. Quinlan, 1984). For this reason, maximum rebound-induced stress levels are not associated with areas of maximum rebound near the centres of former ice sheets but rather with areas where rebound is maximally variable such as the edges of former ice sheets (Walcott, 1970).

Just as it is difficult to be dogmatic about the cause of earthquakes in and near formerly glaciated areas so is it difficult to specify the cause of observed fractures and faults in such areas. Are they due to glacio-isostatic effects and so

of limited duration or are they due to longer-lived tectonic stresses? In this regard it is worthwhile comparing the data on crustal movements from North America with those from Fennoscandia. Both areas are dominated by Precambrian shields that underlie the former centres of several successive ice sheets. Despite these similarities, the crustal movement data suggest that the areas may be quite distinct in terms of their crustal stability. For example, postglacial fault movements on the order of tens of metres are common in the Fennoscandian literature yet the Canadian literature has few reports of fault motion in excess of a few centimetres and none in excess of a few metres. Are these differences real or only artifacts of either insufficient data coverage or improper data interpretation? The next section summarizes the data from North America and Fennoscandia.

2.1 North America

Observations of recent or contemporary crustal movements in northeastern North America have been made since the middle of the nineteenth century. Figure 2 is a map of the area with locations of the references marked on it.

Many clearly-defined Paleozoic faults cut the area of the Appalachians. Some postglacial movements seem to have involved movement along old faults such as the Aspy Fault in NS and the Long Range Fault in southwestern Newfoundland (Grant, 1980b), where shoreline platforms formed before the last glaciation are offset by as much as several metres in the vicinity of the faults. However, close examination of the Oak Bay Fault on the Maine-NB border reveals no evidence of modern movement (Newman, 1979), despite the fact that it lies in a seismically-active zone (Rast et al., 1979).

Most observations of postglacial faulting in northeastern North America are of relatively small-scale features involving a few millimetres or at the most a few metres of vertical offset, along a fold or reverse fault usually no more than a few tens or hundreds of metres long.

In Ontario, all the observations come from the Paleozoic terrane or the southern margin of the Precambrian shield, and most are 'pop-ups' associated with quarrying or other removal of overburden (Coates, 1964; White et al., 1973; Lo, 1978; Adams, 1982). Lawson (1911) and Oliver et al. (1970) felt the faults were related to glacio-isostasy and the latter noted that the pattern of faults in Ontario, Quebec and New York does not accord with present seismicity. More recently virtually all the postglacial faults have been ascribed to horizontal compressive stresses which are a product of regional tectonics.

In Quebec faults are described from the southern parts of the province, in Paleozoic terrane. In the Montreal area, removal of overburden is the dominant theme in formation of faults (Grice,

1972; Saull and Williams, 1974) although observations of faulting which is apparently not connected with construction or quarrying do appear (Chalmers, 1897; Stansfield, 1915). Again, the predominant magnitude and style of recent faulting is similar to that in Ontario, and appears to be best explained as related to regional compression from the east or southeast.

In Atlantic Canada, observations of small-scale faults have been made in the Saint John area (Matthew, 1894) and Halifax area (Goldthwaite, 1924; York and Oliver, 1976), and most recently, Basham and Adams (1984) observed freshly-displaced thrusts associated with the Miramichi Highlands earthquake of 1982. Horizontal compression, which is generally, but not exclusively east-west, is evident in the Atlantic region, as it is further west in New England.

Observations of postglacial faults are numerous in the northeastern part of the US. Early descriptions of reverse faults by Woodworth (1905, 1907), Hobbs (1907, 1911), Cushing et al. (1910) and Decker (1915) are similar to the observations made in southeastern Canada. These have been augmented by recent work which has emphasized the compressive nature of the faults. Block et al. (1979) and York and Oliver (1976) point out that postglacial faults tend to be reactivated older faults or major joints. Some association may be made between bedrock competence and faulting since many of the faults follow along the fissility in shales or other pre-weakened zones (Schafer, 1979; White et al., 1973). Extreme low-angle thrusts in shale bedrock have been noted in New York State where they have been attributed to sub-glacial thrusting in late glacial time (Andrews, 1980).

In both Canada and the US, some faults appear which are normal rather than reverse. Liberty (1969) ascribed such minor features as related to glacial uplift. Loomis (1921) described a very large magnitude fault in Massachusetts with an apparent down-drop of >25 m, based on a dislocation in a glacial lake shoreline. Wold et al. (1977) identified faults in Lake George, NY, from seismic records with vertical displacements up to 24 m. But these observations are exceptional rather than typical for the area as a whole.

Brown et al. (1980), on the basis of accurate geodetic levelling, describe uplifts for the eastern US which are as large as those in the tectonically-active western US. At high elevations in the Appalachians, far south of the formerly glaciated area, up to 20 cm of uplift has occurred in 30 years, and uplift of parts of Florida is as high as 2 cm/year. The curves describing uplift are not smooth but suggest some activity along faults or some zones of concentrated strain. This uplift may be a response to compression which is evident in so many of the faults described in the northeast (Block et al., 1979).

The regional concentration of observations of postglacial faults

is an interesting phenomenon. To some extent it parallels population concentration, and this is an important factor where the observations are associated with pressure release on excavation. It also parallels an important seismic - tectonic phenomenon, the Boston to Ottawa belt (Sbar and Sykes, 1973). This gives weight to the tectonic interpretation of origin for faulting.

Very few observations of postglacial faulting come from the Shield of northern Quebec and Labrador. Lee (1965) observed a number of possible postglacial faults close to the shores of Hudson Bay, and Morner (1979) observed a large number of minor faults on glaciated bedrock surfaces near Poste-de-la-Baleine. Despite the extensive and detailed survey work and observation of glacial lake shorelines in Central Labrador (Harrison, 1963; Barnett and Peterson, 1964), not a single observation of faulting of those well-preserved shorelines exists. Yet the shorelines are warped by differential glacio-isostatic uplift of as much as 0.44 m/km. Similarly, raised marine beaches in northernmost Labrador are deformed upwards to the southwest (Loken, 1962), with no sign of faulting present. Broecker (1966), in his classic work on the deformation of Lake Algonquin shorelines in northern Ontario, also made no observations of faulting along them. One suspects, in all the above cases, that if faults were present on these well-marked shorelines, they would have been observed. Hilaire-Marcel (1980) recognised that postglacial emergence was irregular, consisting of standstills and rapid drops, but ascribed this to a combination of oscillatory, rather than abrupt, isostatic response and eustatic perturbations. He described no instances of faulting connected with the moments of rapid emergence.

2.2 Fennoscandia

Postglacial faulting in Fennoscandia is a hot subject. Since the mid 1970s, Swedish scientists have been embroiled in an argument concerning the tectonic stability of the Fennoscandian Shield and the suitability of the area for siting nuclear plants and for deep disposal of toxic wastes. Prior to this, observations of postglacial faulting were few and limited to western Norway (Feyling-Hanssen, 1966). Following the decision to build 13 nuclear power plants in Sweden, in 1973, considerable effort has gone into investigating the stability of the Shield. Initial generalisations, based on the tectonics of the 1950s (Morner, 1982), were that the shield was stable and suited to such construction, this despite the fact that postglacial glacio-isostatic uplift of Fennoscandia is perhaps better documented there than anywhere. But it was assumed that the uplift was more-or-less complete.

Morner (1977a and b) outlined the past and present uplift of Sweden pointing out that it was and is focused on old faults and large structural welts of known tectonic and seismic significance, such as the 'Hyperite zone' of the south. He

pointed out that detailed levelling of old shorelines shows irregularities which coincide with structures and gravity anomalies. He maintained that postglacial uplift comprised two factors, one glacio-isostatic, which died out about 2-3 ka BP, and the other tectonic, which continues today and is not subject to temporal decrease.

Lagerback and Henkel (1977) described numerous faults in northern Sweden identified from air photographs. They recognised some connection between these and seismic pattern but thought glacio-isostasy was the probable cause. That the faults could be recognized, and traced for over 100 km, is some indication of their magnitude compared with the small features described in North America for the same time. Lagerlund (1977) suggested that 100 m of uplift of the Kullen Hill horst had occurred in southern Sweden in postglacial time.

Bjerhammar (1977) scrutinised the data for Scandinavian postglacial emergence and examined the gravity field data for the Shield. He concluded that there was no direct proof of the existence of tectonic movements in Fennoscandia, and that there is a less than 1% probability that uplift 8 ka BP (clearly glacio-isostatic) and uplift now were due to a different cause. He maintained that glacio-isostatic uplift has not ceased, and suggested that this was not a 'dangerous' kind of crustal instability with respect to the nuclear issue.

Subsequent work has not settled the disagreement between Morner and Bjerhammar, but it may have inclined in Morner's favour on two grounds. First, Husebye et al. (1978) and Bath (1978), analysing the record of Scandinavian earthquakes since as far back as 1497, concluded that tectonic instability is certainly present. Magnitude 6.5 earthquakes have a recurrence interval of about 400 years, and in 1910 there was a sharp break in energy/time release curves for Scandinavia. This accords with global changes, suggesting that global tectonics, rather than local glacio-isostasy, control earthquakes. Secondly, Stephansson and Carlsson (1980) demonstrated that earthquakes and postglacial faults are located within tectonic welts, especially the Tertiary Western Norwegian zone, the Permian Graben around Oslo, and the ancient Lapland zone in the north. They urged for more definitive data on verifying and dating postglacial faults. Some verification has come from the papers by Lagerback and Witschard (1983) and Henkel et al. (1983) who analysed, respectively, the geological and geophysical evidence for the great faults in northern Sweden.

The Parvie Fault (Lundqvist and Lagerback, 1976), to the west of Kiruna, is the largest postglacial fault in Sweden, aligned northeast to southwest for over 150 km. It is faulted up over 10 m on the eastern side and appears to truncate eskers in two locations. There are more than ten other similar faults to the southeast, all similar in trend and type. The Laive-Suijavaara Fault has an apparent vertical displacement of 26 m. Most of the

displacements were measured photogrammetrically, indicative of the scale of the fault scarps formed. This scale causes however some problems in verifying the faults as truly postglacial. Blocks fallen from the hanging wall obscure the detail of many of the faults, and it is impossible to trace the offset of individual scratches or grooves as is possible where the throw is only a few centimetres. Truncation of eskers could have been caused by bedrock irregularity beneath the ice. Geophysical data certainly establish that the faults are present, but do not establish the date of their major activity.

In Scotland, Sissons and Cornish (1982) described differential tilting of blocks in the Glen Roy area from detailed surveying of glacial lake shorelines. The magnitude of tilting is much higher than normally associated with differential isostatic recovery, up to 4.6 m/km, and a fault with 3 m vertical displacement was observed. However, Sissons and Cornish noted the association between the evidence for tilting and the glaciated and flooded areas is complete, suggesting strong glacio-isostatic control.

2.3 North America and Fennoscandia Compared and Contrasted

In eastern North America, faults are typically small thrust or reverse faults, often suggesting compression from the east. They tend to be associated with sedimentary rocks which are for the most part Paleozoic. The movement involved, typically along a zone no longer than 100 m, is usually a few millimetres to a few metres. In shield areas there are very few observations, and those few describe similar very small-scale movements. There is little doubt that most postglacial and probably all modern faulting is tectonic rather than glacio-isostatic in origin.

In Fennoscandia, postglacial faulting is present in Precambrian shield areas and typically involves large scale throws of >10 m along lines often 100 km long. These may be late-glacial, possibly even earlier in age, and there is some evidence that they can all be explained as glacio-isostatic in origin. At the same time, Fennoscandia is not stable in a seismic sense, and Morner may be correct in maintaining that movement in the last 2 ka is tectonic in origin.

Why the difference between the two areas? Although they may appear to be geologically closely related, they do differ in contemporary tectonic setting, belonging to two different, diverging continents. It may be that horizontal plate motions are simply stronger in North America. If this is so, why are there no large-scale post-glacial faults in the Canadian Shield? It may be an artifact of a simple lack of observations in the shield areas of northern Canada. Against this one could argue that it is most unlikely that detailed surveys of shoreline deformation would have failed to uncover some faults if they were there. During August 1985, R. Rogerson travelled the length

of the Labrador coast, partly by fixed wing and partly by helicopter. He saw two areas which might be suitable for ground investigation, where features that looked like fresh (postglacial?) ruptures in bedrock were present. Prior to doing this project Rogerson suggests he would have passed them off as etched out or cleaned off by subglacial water. One area is south of Nain, the other is inland from Eclipse harbour in the far north. Ground investigation of these sites may be considered next year.

Perhaps also relevant to this: recent scrutiny of a 3.5 kHz record of lake sediments obtained in August 1985 from Adams Lake, northern Labrador (063°25'W: 59°01'N), reveals a very clear post-depositional fault through the sediments with a vertical throw of ca. 2 m. A continuing program of surveying the bottom sediments of Labrador lakes may reveal other examples of such faults.

3. Fracture Frequency Due to Glacial Loading, Erosion and Tectonic Stress.

There is no evidence on which to base an evaluation of the relative contributions of glacial loading, erosion and tectonic stress to fracture frequency. Since rocks are weak in tension (tensile strength of 3 to 7 MPa), the tensional stresses that are associated with uplift (Haxby and Turcotte, 1976) could result in fracturing of intact rock. However, most rock masses are fractured and hence the reduction of compressive stress associated with uplift would not result in many new fractures, except at points of stress concentration, but would result in the opening of existing fractures with a corresponding increase in fracture permeability. Walcott (1970) suggests that an ice sheet 2 km thick could increase the compressive stress by about 40 MPa. This increase in stress when added to the existing stress field would be sufficient to exceed the compressive strength of most crystalline rocks but only at depths of 5 km or more.

Field evidence strongly suggests that there is a general increase in fracture frequency near major tectonic features such as major shear and fracture zones. However, modelling studies by Stephansson (1977) showed that moderate increases in tectonic or boundary stresses would not produce major through going fractures in an already fractured rock mass. Also field data (Carlsson et al., 1983) do not show a general change in fracture frequency with depth. However there is a general increase in sheeting fractures in the near surface (< 50 m) and these fractures are assumed to be genetically related to both erosion and deglaciation.

4. Differential Movement of Adjacent Blocks Due to Glacial Loading, Erosion and Tectonic Stress.

This topic is discussed under sections B1, B2 and B3.

5. Changes in Groundwater Systems as a Result of Upward Vertical Movement.

5.1 Changes in Groundwater Systems due to Faulting and Fracturing.

A comprehensive examination by Burdon (1977), of possible mechanisms for maintaining groundwater flow in the long-term absence of recharge has considerable pertinence to the question of vertical crustal motion on groundwater systems. One of the mechanisms considered to be important is that of localized faulting and downdrop of discharge zones, for rejuvenating groundwater flow. This presupposes a similar scenario proposed by Toth (1978, in B5.), wherein exposure of a permeable horizon by erosion can have drastic consequences for regional flow system evolution, causing rapid readjustment to new boundary conditions; in the absence of such an effect, relict hydraulic heads may persist over geologic time scales. Although Burdon only considered faulting of discharge areas, similar consequences could obtain through uplift of recharge areas, or fault-induced juxtaposition of permeable horizons resulting in enhanced deep flow. Such a mechanism warrants consideration in light of information on Holocene faulting in response to deglaciation (eg: Henkel et al., 1983), and raises the possibility of rapid changes in local and regional groundwater flow systems induced by realignment of permeable and impermeable horizons, or by exposure of conductive strata.

Direct evidence of fault-related changes in flow system plumbing was presented by Coltorti and Nanni (1983), where shallow, fresh groundwater in alluvium was observed to be invaded by saline groundwaters of deep origin along faults below, and in, the alluvium. The faults are apparently of Quaternary age, possibly related to Middle Pleistocene uplift and probably reactivated following marine transgression and emergence of the area.

The effect of fault displacement type on hydrogeology was alluded to by Larsson (1972), in which normal and shear faults in granitic rocks were shown to be associated with high and low permeabilities, respectively. Such data can explain the relative rates of groundwater flushing inferred from geochemical studies in sheared and unsheared granitic rocks (eg: Jacks, 1972; 1973; in B6.1.), and may help to explain the localized, or patchy, occurence of pockets of saline groundwater in some areas of Sweden (eg: Allard et al, 1983, in B6.2).

5.2. Changes in Groundwater Systems due to Regional Strain and Tectonic Movements.

Bradley (1975) presented a comprehensive discussion of causes of abnormal fluid pressures, and concluded that the most important factors are: 1) epeirogenic movement; and 2) temperature change of the fluids. Other possibilities, such as osmotic pressure, chemical precipitation/solution, overburden stress and transients (seismic, tidal, barometric) are not considered important. Epeirogenic motion is a particularly important factor, since it can create an "inherited" or relict hydraulic head distribution which can differ substantially from the hydrostatic head expected from present topography (cf: Toth, 1978; in B5.). On the other hand, Berry (1973) dismissed relict pore pressures as a possible cause for abnormally high pressures observed in the Great Valley, California. Instead, he contended that lateral compressive stress due to plate motion is responsible for elevating fluid pressures in shales being compressed between granitic blocks in this region. Abnormal pore pressures in these rocks are estimated to represent late Cenozoic compression.

Goguel (1978), although discussing tectonically-induced abnormal pressures only in generalities, is one of the few authors to distinguish transient versus long-term overpressure. The distinction becomes important in classifying processes which alter a flow system's boundary conditions and which can lead to relatively rapid or very slow changes in flow patterns.

Although vertical crustal motion is explicitly dealt with only by Bradley (1975), the case presented by Berry could be extrapolated to vertical compressive situations involving shales or similar low-permeability units. However, extrapolation to crystalline rock environments would be risky, since none of these authors discuss their conclusions on the bases of their arguments in quantitative terms.

5.3. Changes in Groundwater Flow Systems due to Erosional Unloading.

Perhaps the largest amount of information available on the effect of vertical crustal motion on groundwater flow, is related to erosion-induced changes in flow system boundary conditions. Menely et al. (1982), in an important summary article, stressed the need to understand the effect of erosion on regional flow systems, recognizing that glacial erosion and isostatic rebound have profoundly affected regional groundwater flow. In this regard, two schools of thought have evolved, differing in the perceived importance of the elastic properties of the porous medium and the resultant sign of the pressure differential due to unloading. Historically, it appears that sub-normal pressures related to unloading have dominated geologists' thinking, with only the relatively recent introduction of over-pressure as a possible and viable

consequence of erosional unloading, at least on the regional scale.

Dickey and Cox (1977) reviewed the occurrences of sub-normal pressure and postulate erosional unloading of confined porous strata as the cause. Russell (1972) documented the occurrence of under-pressure in Appalachian reservoirs and postulated that the unloading of shales initiated pore pressure decline, which was subsequently transmitted to adjacent reservoirs. The first quantitative evaluation of the basic hypothesis is due to Neuzil and Pollock (1983), who showed that rocks with low hydraulic diffusivity could be expected to develop very large pore pressure declines under realistic erosion (unloading) rates. Their analysis was based on the one-dimensional form of Terzaghi's consolidation-rebound equation:

$$\frac{K\partial^2 h}{S_o \partial z^2} + \frac{\alpha v}{S_o}\frac{\partial \sigma v}{\partial t} = \frac{\partial h}{\partial t} \qquad (1)$$

For a surface rock unit of 1,000 m thickness, undergoing 10 cm/1,000 yr erosion, with $K/S_o = 10^{-9}$ m^2/s, and a lower boundary maintained at hydrostatic pressure, a negative pore pressure of ca. 5-10 atm. could be expected after 4-5 Ma. Neuzil and Pollock claim that this is the only realistic manner in which to predict the effect of erosional unloading, that is, by taking into account the deformability of the porous medium. The authors suggest that their analysis "may pertain to some crystalline rocks" with very low hydraulic diffusivity.

On the other hand, Toth (1978) showed in a convincing and very well-documented study of a regional flow system in Alberta, that over-pressures were present in a deep Devonian aquifer, which could be explained by preservation of relict Pliocene hydraulic heads. Erosional exposure of a Cretaceous unconformity during the Pleistocene served as a drain for the upper hydrogeologic units, leading to the very slow dissipation of the deep aquifer's Pliocene hydraulic head through an overlying aquitard. Based on the one-dimensional non-steady flow equation (to which equation (1) reduces for constant vertical stress, σv):

$$\frac{K\partial^2 h}{S_o \partial z^2} = \frac{\partial h}{\partial t} \qquad (2)$$

the required time to dissipate this excess head is of the order of 4 Ma. Since only 0.3 - 1.3 Ma have elapsed since the erosional exposure of the unconformity "drain", the observed pore pressures represent ca. 20-85 percent of the relict Pliocene heads. The major implication of this work is that relict heads can be preserved over geologic time scales, but also that very major changes in a flow system's dynamics can be initiated by relatively minor erosional changes at the surface.

The divergent conclusions of Neuzil and Pollock's versus Toth's work impact directly on the study of deep groundwater flow

systems in the context of waste disposal. Erosional unloading in the Neuzil view would result in reduced pore pressures and flow of water into affected rock masses, a desirable consequence for waste management. On the other hand, Toth's contention is that erosion, in a regional sense, would always cause flow system readjustment by outward flow, but with the time scale of readjustment critically dependent on where and how erosion modified the geologic section.

Neuzil (1985) criticized the work of Toth and a companion paper by Toth and Millar (1983, in B6.3) on the grounds that the inference of relict excess pore pressures was unfounded because it did not take into account elastic deformation of the porous medium, as did Neuzil and Pollock's (1983) work. Toth and Millar (1985, in B6.3) responded that the assumptions underlying Neuzil's use of the consolidation equation and the data available on hysteresis properties of rocks, as well as the uncertainty involved in assigning appropriate parameters to the complex sequence of rock types in their study area, and the fact that over-pressures, not under-pressures are observed in their study area, argue against the application of Neuzil's theory to their particular regional flow system analysis. Obviously, the question of the sign of the pressure effect associated with erosional unloading must be rated high on a priority list of topics pertaining to groundwater flow and vertical crustal motion.

6. Readjustment Time of Groundwater Systems Due to Changes in the Geological Environment.

6.1 Groundwater Readjustment Time Pertaining to Faulting and Fracturing.

Direct evidence or estimates of time required for flow system readjustment due to faulting are scarce. Burdon (1977, in B6.1) considered that fault-induced changes in discharge levels would be an effective means of rejuvenating groundwater flow in the absence of contemporary recharge. Presumably, fault displacement could lead to a relatively rapid, short-term readjustment, depending on the magnitude of the displacement and the rate of fault displacement.

Although the data presented by Coltorti and Nanni (1983, in B6.1) do not permit age inferences to be made on the deep, saline fluid presently leaking from faults in alluvial fans, geological evidence suggests that these fluids are "fossil", and that faulting was probably initiated during Pleistocene uplift of the area.

Fault zones in granitic rocks of Sweden and Scandinavia are commonly associated with high permeabilities, and commonly contain waters which are much less saline than fluids in the

bulk of the surrounding "tight" crystalline rocks (eg: Allard et al., 1983; in B6.2). Jacks (1972, 1973) showed that the salt content of these groundwaters was due to a marine source, inferred to be relict Baltic Sea water emplaced when the region was isostatically depressed. Groundwater flushing of this saline water in the topmost 100 metres has occurred in the past 5,000-10,000 years, giving an indication of the time required for groundwater in such rocks to adjust to new input sources. Furthermore, fluids associated with sheared and faulted zones in these rocks are often depleted in salt content at depths greater than 100 metres, indicative of the high permeabilities in such zones, and pointing to much more rapid readjustment of these localized deep zones to changes in the fluid regime. In a qualitative manner, then, the salt content of these groundwaters indicates the time scale for readjustment of the groundwater system to changes in input.

6.2. Groundwater Readjustment Time Pertaining to Regional Strain and Tectonic Motion (including Glaciation and Deglaciation).

Chemical data are almost exclusively used in estimating or inferring fluid ages in low permeability crystalline rocks. The existence of saline groundwaters in Scandinavian coastal areas below a depth of ca. 100 metres has generally been considered the result of Baltic Sea water encroachment 3,500 - 8,000 years BP during the last glacial isostatically-depressed regime (Allard et al, 1983; Lahermo and Lampen, 1985; Jacks, 1972, 1973, in B6.1), relict igneous fluids (Nordstrom, in Allard et al, 1983), or unspecified fossil sources (Laurent, 1982, in B6.4). Carbon-14 analyses generally indicate ages of the order of 10^4 years. These time frames thus give a rough estimate of the age of the water. Qualitatively, chemical contrasts between these fluids and shallow, fresh groundwaters indicate the relative residence times and rates of flushing of the deep and shallow parts of the system, following emergence of the Scandinavian Shield and subsequent meteoric water input.

Interestingly, the occurrence of saline waters in Scandinavian crystalline rocks is notably discontinous, as for example, Jacks showed (1972, 1973, in B6.1). Allard et al (1983) observed that saline waters could be found in close proximity to, and even surrounded by, fresh waters at the same depth. This patchy distribution of saline waters indicates 1) that the rates of flushing of adjacent blocks of crystalline rock can differ greatly (eg: due to fault control?); and 2) a very slow exchange of fluid between the saline and fresh water pockets characterizes this rock environment.

Of considerable importance in evaluating the response time frame of these groundwaters is the hypothesis by Jacks (1978), that the incursion of Baltic Sea water into coastal granitic rocks of Scandinavia is not the cause of elevated salt concentrations in

these groundwaters. Rather, he considered that marine clays, deposited over the submerged coastal shield rocks, only later became the source of salt input to the crystalline rock aquifers after renewed meteoric recharge dissolved these salts and flushed them into the underlying rocks. Subsequently, removal of the clays as a salt source and/or dissolution of all their available salts, lead to renewed fresh water recharge of the system, with concomitant flushing of the shallowest and most permeable zones. In this view, the response time of the crystalline rock hydologic system to changes in salt input may be considerably shorter than inferred simply from the time of emergence of this part of the Shield. In particular, Jacks noted that the present location of saline groundwater would necessarily be patchy, owing its existence to the areal distribution of postglacial marine clays, as well as to low altitude and low permeability, and that this "patchiness", too, would therefore not be long-lived.

6.3. Groundwater Readjustment Time Pertaining to Erosional Unloading.

Some of the most recent and most pertinent data on estimated response times of groundwater flow in granitic rock has come from studies of the Illinois Basin deep drill hole (Couture et al., 1983; Couture and Seitz, unpublished manuscript). High salt concentrations in groundwaters found in the granite basement are inferred to be due to extensive lateral migration of formation fluids out of the Illinois Basin ca. 200 Ma BP. Chloride concentrations in the granite presently range from 2.7 moles/litre some 600 metres below the granite-sandstone contact, to near zero at the contact, and are monotonically correlated with depth. Fission track data and oxygen isotope data combined, indicate that erosion of much of the sediment cover occured about 130 Ma BP, and probably coincided with fresh groundwater replacement of the formation fluids in the sandstone at about the same time.

Simple diffusion calculations suggest that diffusion of salt out of the granite into the actively circulating sandstone aquifer could account for the observed chloride profile in about 130 ma, but not less than 11 ma. The very low permeabilities of the granite (10^{-16} to 10^{-17} m^2), the apparent fit of the chloride profile to a diffusion type profile, and the agreement of calculated diffusion times with independent estimates of the time of initiation of groundwater flushing of the sandstone, lend considerable credence to the very long times for removal of salt from the upper part of the granite basement. Such calculations point out the extreme sluggishness of tight crystalline rocks to respond to major changes in the overlying hydraulic regime.

The possible role of relict hydraulic heads in regional flow system evolution was raised by Burdon (1977, in B.1), who calculated for a model basin (porosity = 5%, transmissivity =430

m/day) that even after 10^4 years, some 17 percent of the original head remained to drive the system in the absence of recharge. Toth (1978, in B.3) compiled extensive data showing that abnormal over-pressures in north-central Alberta represented relict Pliocene heads, suggesting that groundwater response time to erosional changes in boundary conditions could be in excess of 1 ma. Subsequently, Toth and Millar (1983) refined these estimates, but the conclusion remained that groundwater response in this case was over geologic time scales. Such long response times are in sharp contrast to the relatively rapid reponses expected for some fault-induced changes, such as exposure of previously confined porous strata, for example as proposed by Burdon (1977, in B6.1). The long response times characteristic of the Alberta basin system appears to be critically dependent on the low permeability of confining strata overlying the over-pressured formation. Whether the general conclusions of this study might apply to the crystalline rock environment, depends on the relative permeabilities involved, and presumably also on the degree of vertical anisotropy which may be encountered on a regional scale in the Canadian Shield (cf. Menely et al, 1982, in B6.3).

6.4. Assessment and Dating of Groundwater Associated with Unspecified Processes.

Growing awareness in the past five years, of unusual brines which exist at great depth in the Canadian Shield and other cratonic crystalline rock environments, has focused attention on the information to be gained from studies of these fluids. In particular, Meneley et al (1982, in B6.3) recommended further research on salinity/depth relationships in groundwaters, and the origin(s) of deep brines in crystalline rocks. Potentially, such work may answer such questions as the age of deep groundwaters in crystalline rocks, the origin and evolution of such fluids, and the response of these fluids to perturbations such as epeirogeny, deep crustal magmatism, faulting and regional tectonic stresses. Geochemical work done to date on these and other saline groundwaters in crystalline rocks, as well as on fracture-filling minerals, and fluid inclusions, promises to give much new information on the origins and ages of such fluids. For a recent summary of current literature on brines and groundwaters in crystalline rocks, the review by Johnson (1982) is recommended.

Studies of the saline groundwaters occurring at depths of 100-200 metres in the Scandinavian Shield generally points to considerable age of these waters (eg: Laurent, 1982). Laurent presented an excellent set of data, including carbon-14, uranium isotope ratios, and dissolved gases, supporting this thesis. Good to excellent agreement between ages inferred from all these sources strongly suggests that these saline waters represent mixtures of modern meteoric and fossil (>·10,000 yr) waters. In

light of stable isotope data derived from much more concentrated brines (see below), the lack of any stable isotope shift in these comparatively dilute saline waters is also noteworthy.

Data on highly saline brines in crystalline rocks (exceeding 100,000 ppm Total Dissolved Solids) currently derive mainly from studies on the Canadian Shield (eg: Fritz and Reardon, 1979; Frape and Fritz, 1981). These and numerous other authors have considered these brines to be "many thousands of years" old. Fritz and Reardon (1979) hypothesized that "active flushing of the lithologic sequences of their pre-Pleistocene formation waters had begun only in the past several tens of thousands of years"(our emphasis). Although these authors do not venture to speculate on the cause of such renewed flushing, one obvious possibility would be related to glacial rebound.

Commonly proposed origins for these brines include paleoformation waters or relict marine water, fossil meteoric water altered by very long water-rock interaction, and residual igneous/ metamorphic fluids. No one hypothesis appears to satisfactorily explain all the brines' properties; their very unusual stable isotopic compositions are a good example. The deuterium and oxygen-18 isotopic enrichments which characterize these brines cannot be derived from any meteoric, marine or formation water, but can be explained by clay mineral formation or production of reduced gases, processes which would require considerable time at low temperature, but which would be consistent with the inferred great age of these fluids. Thus, the lack of any stable isotope shifts in the relatively dilute Scandinavian saline groundwaters would be consistent with their inferred age of ca 10,000 yr (eg: Jacks, 1972; 1973, in B6.1).

Finally, special attention should be given the observation that although these brines are widespread and commonly encountered in deep mines (> 2 km) on the Canadian Shield, freshwaters also are commonly found at the same depths (Frape and Fritz, 1981). The observation of high carbon-14 activities in many mine drill holes at great depth implies that disturbance of the natural rock environment by mining leads to very efficient, and very deep, circulation of modern groundwater. Thus, these crystalline rocks apparently can be disturbed artificially, demonstrating a very rapid response of groundwater flow to such perturbations.

In closing this discussion of groundwater response times to perturbations, the topics of fracture-filling mineralization and fluid inclusions must be mentioned. In recent studies which have focused on the recent history of rock masses from a waste disposal viewpoint, some potentially important data have been reported which bear on the history of the fluid circulating in the rock mass. In particular, the studies by Tullborg and Larsson (1982, 1983) showed that combined fluid inclusion and geochemical work on fracture minerals could distinguish different episodes of fluid involvement, different sources of fluids, and from age estimates of fracture mineralization, the

probable late history of rock-water interaction. Thus, Tullborg and Larsson (1982) were able to conclude that one of the last generations of calcite in fractures was of Quaternary age, probably precipitated from a mixed freshwater-Baltic seawater fluid, with fresh water calcite deposition continuing possibly to the present. Similarly, Kerrich (1984) showed through oxygen isotopic analysis that all fluids involved in the Eye-Dashwa Lakes fracture mineralization were of pre-Pleistocene age, although late clay-coated (low-T) fractures "may have formed in equilibrium with recent surface waters".

D. EVALUATION OF INFORMATION ON VERTICAL CRUSTAL MOVEMENTS PERTAINING TO DEEP DISPOSAL.

The overall task of this study was to evaluate the information in the published and unpublished literature on vertical crustal movements due to glacial, erosional and tectonic events in order to determine if there is justification for a detailed analysis of the effects of vertical uplift on bedrock and on ground water as they pertain to the deep disposal of radioactive waste. Our review has shown that, while the geological record and observational data are incomplete, vague and in places contradictory, vertical movements have taken place during the Cenozoic. The published record suggests that vertical and differential movements that have resulted from uplift due to glacial unloading are significantly greater than those that are erosionally induced. The relative contribution of tectonic stress to the observed vertical movements cannot be clearly defined. However in selected areas there is a tentative spatial correlation between seismic activity and observations of vertical movements. What is needed is to calculate the level of postglacially-induced stress for many areas within Canada and compare these levels with the rate of seismic activity in order to determine if postglacial rebound acts as a trigger for tectonic stress release. It should be noted that the reduction in normal stress, on discontinuities, associated with uplift will increase the deviatoric stress and allow shear displacement to take place. Also it is generally agreed that in eastern Canada the effects of glacial uplift are decreasing.

In general we feel that vertical movements follow existing fractures or faults, a process of rejuvenation rather than the creation of new conduits. Where new fractures are created as a result of stress concentrations, they are thought to be of limited extent. While the existing numerical model studies of stress distributions in fractured rocks are of a preliminary nature, they have supported the above conclusions.

An area of major concern in the literature is the apparent order of magnitude difference in the magnitude and frequency of recent vertical movements in Fennoscandia versus those reported for North America. It is recommended that the existing data base be strengthened by limited field checking of selected sites in North America followed by field checking of one or two sites in Sweden. These field checks should be undertaken by a specialists in the appropriate fields

The literature supports the view that long transients can exist in ground water flow systems. However the supporting data come primarily from sedimentary rocks and may not be directly transferrable to the fractured crystalline bedrock environment. In addition the existing observational data base is difficult to interpret and suggests that local erosion can play a major role in both short-circuiting and rejuvenating flow systems. There is a real need to reconcile the distribution of relict or existing

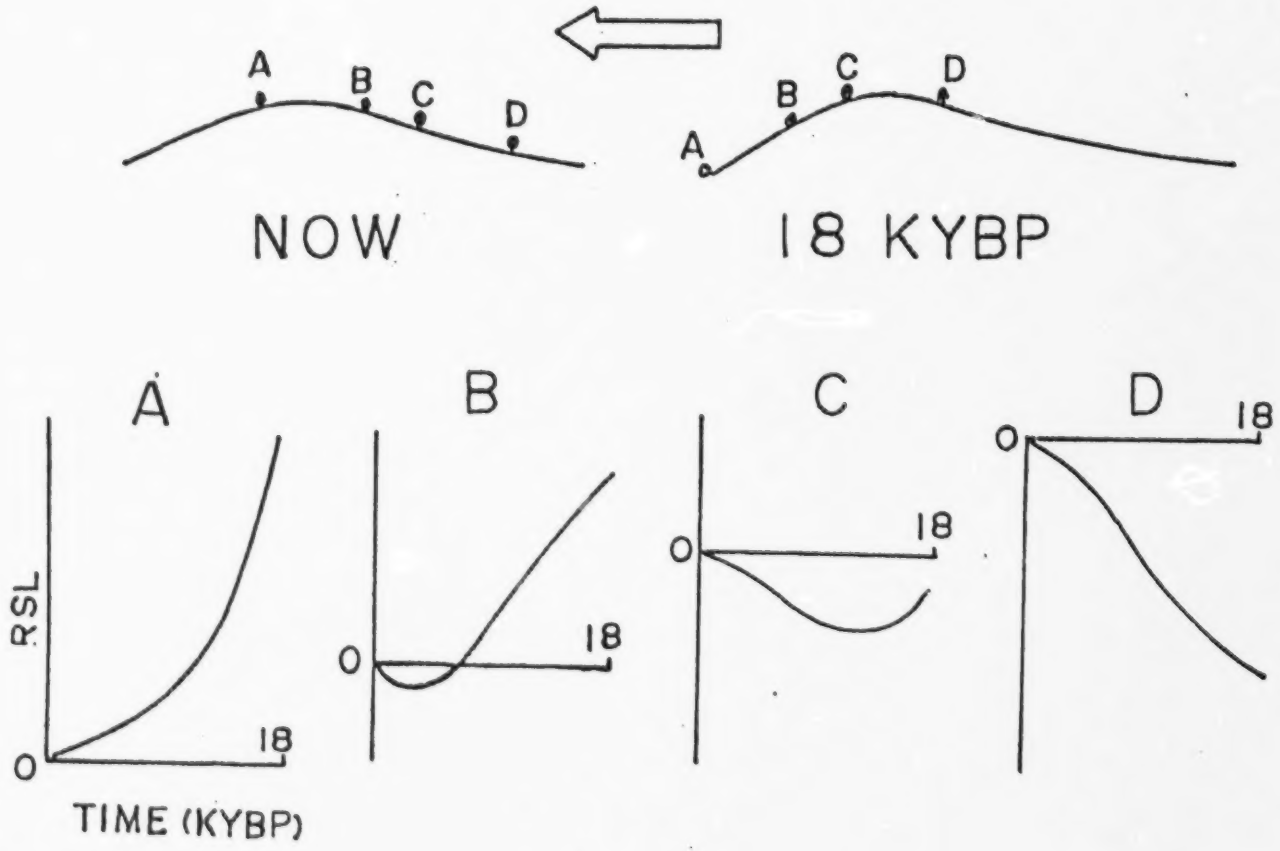
hydraulic heads in paleosystems with the stress changes induced by both erosion and uplift. What is lacking is a fairly rigorous interpretation of the existing paleo-flow system data base taking into account current glacial-isostatic theory and both erosion and glacially-induced uplift.

In summary; 1) the literature is sufficient to define the range of the displacements that have taken place on discrete fractures, 2) the basic theory on glacial-isostatic movement is sufficiently well developed to enable one to define the horizontal and vertical (depth) extent of such movements along existing discontinuities, 3) sufficient laboratory data on fracture mechanics (properties) and the stress-fracture permeability relationships exist to approximate the impact that movements of the magnitude observed would have for different contractant and dilatant conditions on the permeability of discontinuities in fractured crystalline rocks, 4) existing three-dimensional numerical models provide an adequate tool with which to analyze the impact of vertical crustal movements on existing groundwater flow systems.

FIGURES

Figure 1. Conceptual model for glacial-isostatic rebound.

Figure 2. Location of study areas described in this report.



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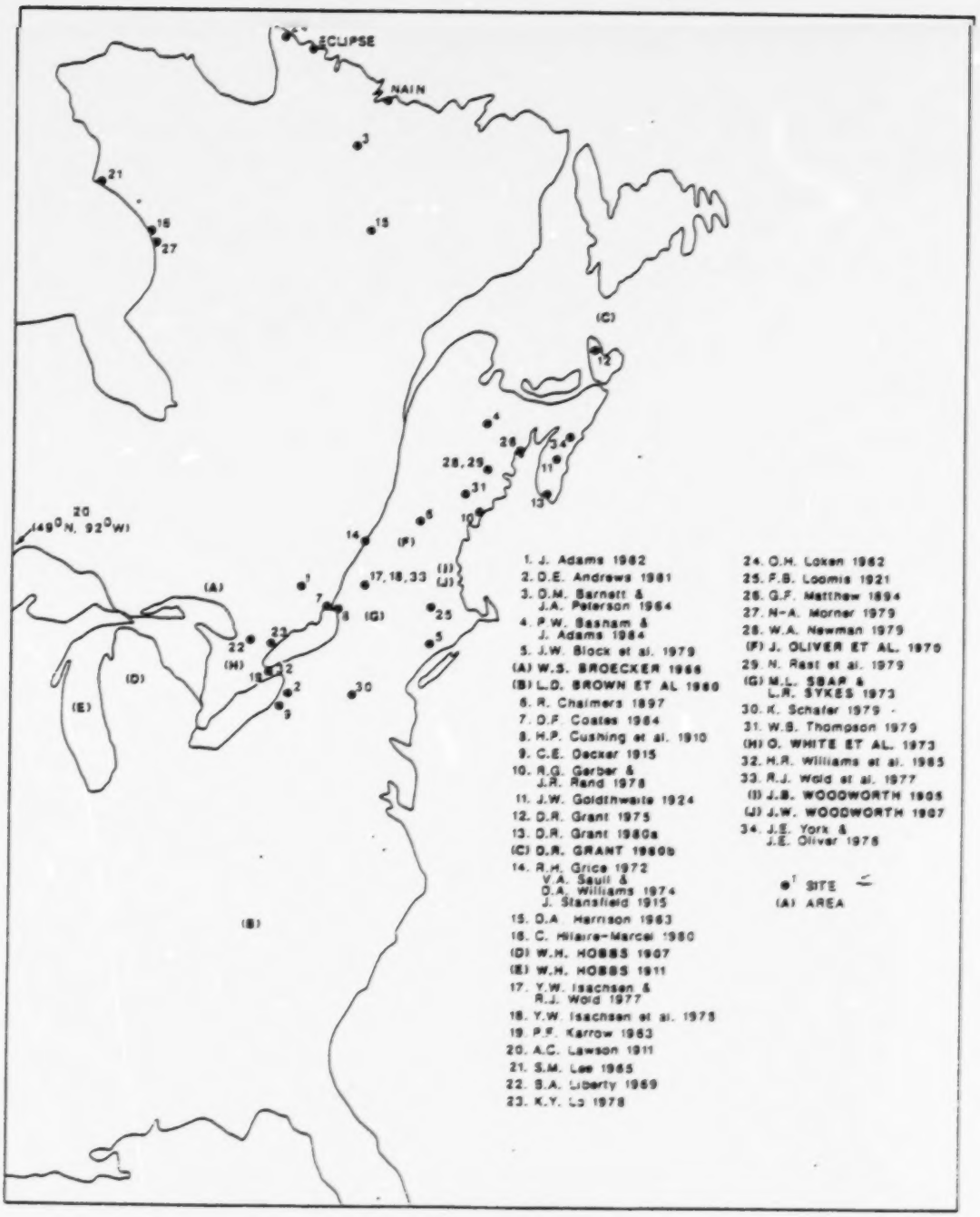

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